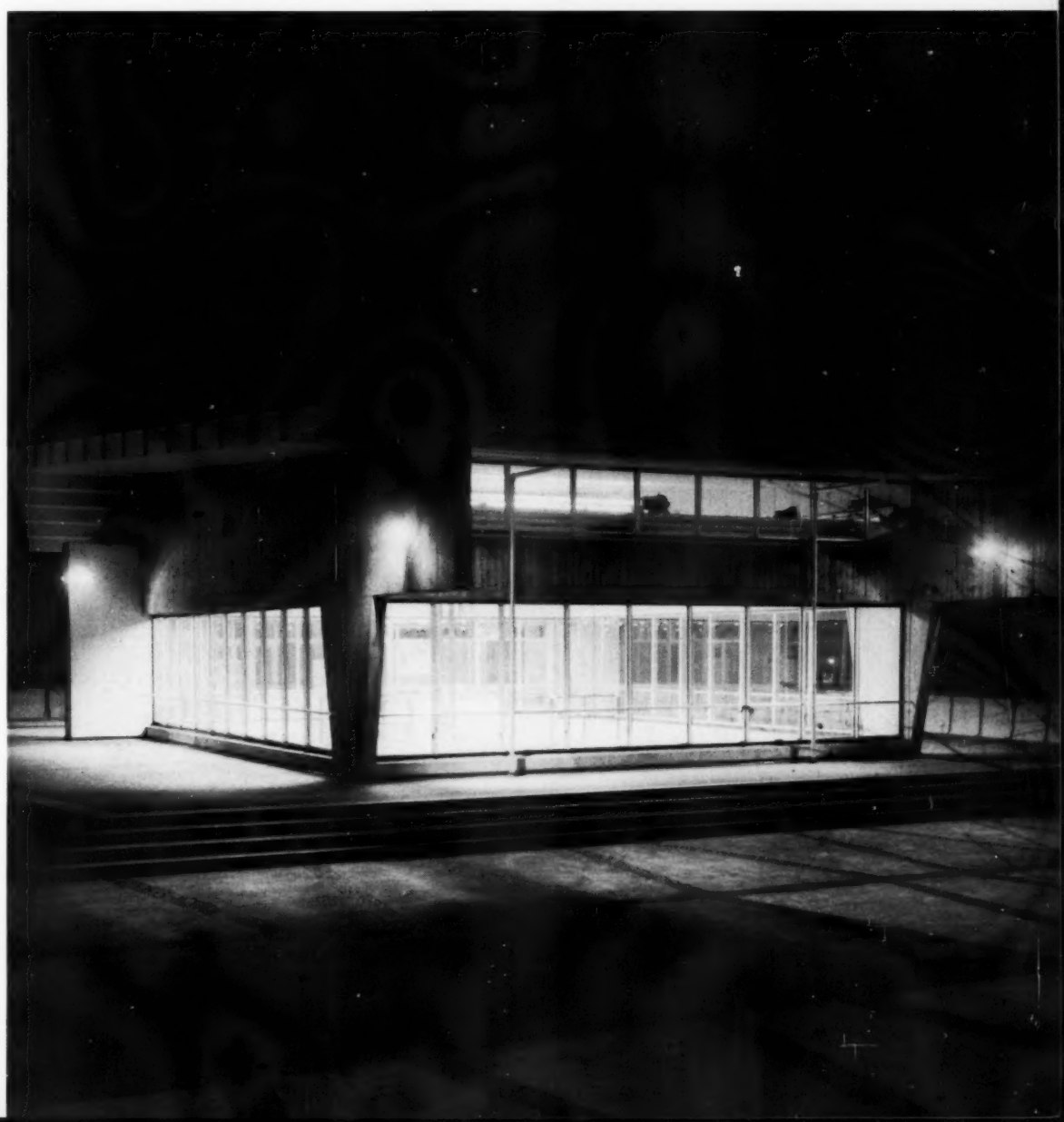
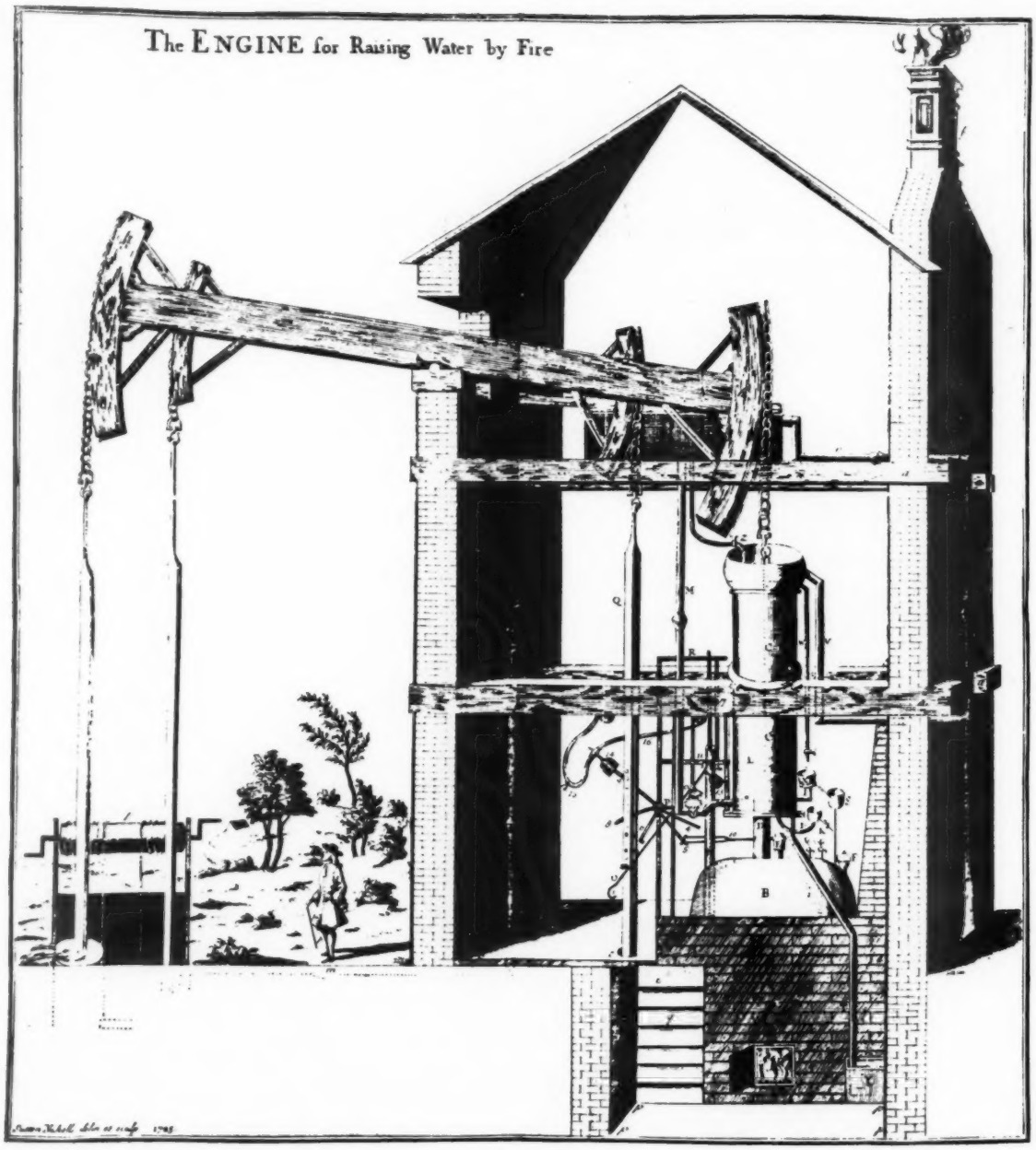
THE TREND IN ENGINEERING

at the University of Washington

Special Issue—July, 1961

• UNIVERSITY CENTENNIAL YEAR •





Newcomen's Single-Acting Atmospheric Engine. This bulky predecessor of the nuclear reactor was used for half a century to pump water from English coal mines. The machine, developed between 1705 and 1725, was the first true steam engine. In it Newcomen improved upon Savery's 1698 patent; then, over a generation later, Watt added to the engine the condenser needed to improve its efficiency.

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IN ENGINEERING

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Vol. 13 No. 3

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COVER

Seal. The Centennial Seal was designed to Commemorate the 100th anniversary of the University of Washington, which this double issue of *Trend* celebrates.

Picture. The photograph is a night view of the Nuclear Reactor Building, the newest engineering building. On April 10 the Teaching Reactor it houses was put into operation.

The First Century

HAROLD E. WESSMAN, *Dean of the College of Engineering*

On behalf of the faculty of the College of Engineering I am happy to introduce this issue of *Trend* as a part of the celebration of the University of Washington Centennial Year. The University is now 100 years old, and we are on the threshold of the second century. As we look back to 1861, it is difficult to believe that here, in what was then the Far Pacific Northwest, an institution dedicated to peace and learning initiated its program in the same year that witnessed the beginning of a terrible Civil War that almost wrecked our nation. The University opened its doors in a little schoolhouse located in downtown Seattle where the Olympic Hotel now stands. There were 37 students and one teacher. Now, in 1961, we have over 18,000 students and over 1,000 faculty members.

Almost 40 years passed before the College of Engineering became a recognized unit of the University. The first dean, Almon H. Fuller, was appointed in 1899. Degree programs were soon under way in Civil, Electrical, Mechanical, and Chemical Engineering. Aeronautical Engineering was established in 1929.

Dean Fuller served from 1899 to 1917. He was succeeded by Carl E. Magnusson, who served until 1929. Richard G. Tyler then served for six years, from 1929 to 1935. He was followed by Edgar A. Loew, who served for thirteen years, from 1935 to 1948. The writer has served as Dean since 1948.

Although instruction in Mining Engineering was begun in 1893, it was not until 1911 that a College of Mines under the direction of Dean Milnor Roberts was authorized with programs in Mining, Ceramics, and Metallurgy. When Dean Roberts retired in 1947, the College of Mines was merged with the much larger College of Engineering, and its name was changed to the School of Mineral Engineering.

The College of Engineering has grown rapidly through the years, until it is now the largest engineering school on the Pacific Coast. The faculty, exclusive of research staff, number 170. The student body includes 2,250 undergraduates and 600 graduate students. All departments offer bachelor's, master's, and doctor's degrees except Mining and Ceramic Engineering, in which graduate programs are limited to the master's degree. In addition to the degree departments, there is a Department of General Engineering to which all freshmen are assigned for the first year of their undergraduate work. There is also a Humanistic-Social Studies Department serving engineering students only.

In 1955, the College established a graduate program in Nuclear Engineering, and the first degree was granted in 1958. Courses in this program now involve seven different laboratories. A major facility, the University of Washington Nuclear Reactor housed in the building shown on the cover of this issue, was dedicated June 1, 1961.

This Centennial Issue is focused primarily on recent research projects in the various engineering departments. These projects briefly described in the following pages are indicative of the many research programs that have not only served to advance the frontiers of knowledge in all branches of engineering but have also contributed to the industrial strength of the Pacific Northwest.

The undergraduate and graduate programs of instruction in the College have undergone a searching and critical review during the past five years. In line with national trends, more courses in the basic sciences, in mathematics, and in the engineering sciences have been introduced. Analysis and design courses have been revised to reflect the latest contributions. All are constantly incorporating new knowledge.

As we enter the second Century, the College of Engineering is dedicated to its responsibility of educating young men for the engineering profession, a profession which differs from that of the pure scientist by its constant emphasis on the creation of useful products and products at the lowest cost consistent with safety. In discharging this responsibility, however, the College recognizes that the best engineer of the future is one who uses all of the scientific tools available in the most effective manner. Consequently, fundamental education in engineering must incorporate a more thorough background in science, particularly in mathematics, physics, and the engineering sciences, such as Mechanics of Solids, Mechanics of Fluids, Thermodynamics, and Materials Science.

Our mission is four-fold: (1) to provide a strong undergraduate engineering education leading to the bachelor's degree that will enable some students to enter the profession with sufficient background to make them immediately useful in certain types of positions and for others to enter into graduate study; (2) to provide a stimulating program of graduate studies and research for students with the potential to complete such a program successfully; (3) to permit the outstanding student to realize his full capabilities and develop those qualities that will eventually make him a leader in the profession; and (4) to inculcate in all of our students the desire to read, study, and progress professionally "on their own" in their chosen field after graduation.

DEANS OF ENGINEERING, PAST AND PRESENT: ABOVE, FROM LEFT TO RIGHT, A. H. FULLER, R. G. TYLER, E. A. LOEW, AND H. E. WESSMAN. LEFT, C. E. MAGNUSSON.

BELOW, TOP CENTER, OLD ENGINEERING HALL: The College of Engineering inherited this building, its first home, which had served the Alaska-Yukon-Pacific Exposition as Machinery Hall. It was torn down to make room for the Mechanical Engineering Building, completed in 1959. On the left is the entrance to the Electrical Engineering Building, completed in 1948; on the right, a structural-research laboratory which included the suspension-bridge wind tunnel. It stood on ground now occupied by the new Nuclear Reactor Building.

The Growth of Research Potential in the College of Engineering

F. BURT FARQUHARSON, *Director, Engineering Experiment Station*

Historical Sketch of the University: First Half (1861-1911)

"The University of Washington is the oldest institution of learning north of the Columbia River. July 17, 1854, Congress donated to the Territory of Washington two townships of land for the purpose of establishing a university. The legislature located the University at Seattle, July 29, 1855." During the next six years the territorial legislature vacillated, and no decision was reached on competing sites until the winter session of 1860-61 settled the matter by locating the University in Seattle. The following condition was imposed: "provided a good and sufficient deed to 10 acres of land eligibly situated in the vicinity of Seattle be first executed to the Territory of Washington for University purposes."

A. A. Denny, C. C. Terry, and Edward Lander donated the ten acres presently occupied by the Olympic Hotel and several other valuable properties. On May 20, 1861, the cornerstone of the University building was laid with appropriate ceremonies. In the autumn of 1862 the buildings were completed, and during the winter the University was opened.

At an early date in the history of the University a demand arose for instruction in engineering and mining. In view of the meager support from the territorial legislature ($34,350 during the first 27 years), it is not surprising that growth was slow. Not until 1897 was a full course of studies in Civil, Electrical, Mechanical, and Mining Engineering offered. The following year found 18 students registered, and by 1900 the number enrolled had risen to 44 and those in Mining to 35. The first B. S. degree in Mining Engineering was awarded in 1900, in Civil Engineering in 1901, in Electrical Engineering in 1902, in Mechanical Engineering in 1906, and in Chemical Engineering in 1907.

The 1900 catalog records a faculty of 24 in the College of Engineering and the School of Mines, including 7 instructors and 2 lecturers in "Mining Law" and "Irrigation and Water Rights." The full-time engineering staff numbered only eight individuals, with the remainder of the instruction provided by the various divisions of the College of Liberal Arts.

By an act of the Legislature, March 14, 1893, the University was relocated at it present site, which embraces 350 acres. The transition was not made until September, 1895, pending the clearing of building sites and construction of new facilities. The legislature of 1893 appropriated $150,000 for new building and improvement of the new grounds, and $39,000 for maintenance for two years; that of 1895 appropriated $50,000 for additional buildings and improvements and $90,000 for maintenance for two years. A law was also enacted providing for the bonding of the University lands for $225,000 to be paid into the general fund of the state, so that $225,000 of the above generous appropriations was really a loan to the University advanced at this time to place the institution on a broad, substantial foundation.

The Alaska-Yukon-Pacific Exposition, held on the campus in 1909, focused world-wide attention on the University and left a number of substantial buildings that solved many space problems as the institution continued to grow. A significant number of these structures were extensively remodeled and some are still in use. The building known as Machinery Hall during the exposition became the center of engineering activity. For many years it housed the departments of Civil, Electrical, and Mechanical Engineering. The Good Roads Building was used for lectures and laboratories in connection with highway construction. The new forge and foundry building was well equipped for instruction in Mechanical Engineering. The old brick power house on the shore of Lake Washington was converted into a hydraulic laboratory operated by the Civil Engineering department. The Mines building was a two-story structure formerly occupied by the University power plant and machine shops. The interior was remodeled to accommodate the machinery and apparatus, as well as the office and lecture rooms of the School of Mines.

In 1905 the Federal Government established a Timber Testing laboratory in the College of Forestry and in 1909 added a Wood Preservative laboratory followed in 1911 by a Wood Distillation laboratory. The students in the College of Forestry were required to register in a number of courses in Civil and Mechanical Engineering. In the use of equipment, a free interchange existed among Forestry, Civil Engineering, and Mechanical Engineering.

In 1911 the Engineering Faculty numbered 18, and the total registration was 331; 33 degrees were granted during the year. During the period 1902-1911, eleven faculty publications are on record, one each from Forestry and Mines and nine from the College of Engineering.

The Second Half (1911-1961)

Interim Period (1912-1930)

This was a period of intermediate growth during which a substantial faculty was accumulating and the student body was growing at a healthy rate. The total engineering registration in 1912 was 384, and

39 degrees were granted. By 1930 the enrollment had grown to 1093, with 69 degrees awarded.

In January, 1916, the Board of Regents authorized the establishment of a Bureau of Industrial Research in order to coordinate an expanding program of research in industry, at this time largely confined to Chemical Engineering.

In December, 1917, the Board of Regents changed the name of the Bureau of Industrial Research to the Engineering Experiment Station and appointed a governing board consisting of the President, the Dean of the College of Engineering, the Director of the Station, and one representative from each engineering department and from Physics and Forest Products. The Station was established to coordinate investigations in progress and to facilitate the development of engineering and industrial research in the University. Its purpose was to aid in the industrial development of the State and the nation by scientific research and by furnishing information for the solution of engineering problems. Prior to the organization of the Station, a total of 92 technical publications in various journals was recorded. During the next 13 years the Station published 54 bulletins and two reports.

In 1916, the Northwest Experiment Station, one of 12 research laboratories set up by the U.S. Bureau of Mines, was established on the campus.

During this period the research facilities of the institution were strengthened by the addition of the Boeing Aerodynamic Chamber (a 4-ft. wind tunnel) in 1918, the Forest Products Laboratory in 1921, and Guggenheim Hall (the Aeronautics Building) in 1930.

Period of Stress (1931-1947)

This period started at the depth of the depression and carried through the war years. The total registration in 1931 was 1030, and 115 degrees were granted. In 1947 the registration had grown to 2142 and the degrees to 208. The number of Experiment Station Publications during these years totaled 66.

By special bill the 1945 legislature provided $24,000 to be used during the 1945-47 biennium to subsidize 10 Graduate Research Fellowships per year for the biennium. The integration of this new effort in the College of Engineering became the duty of the Director of the Engineering Experiment Station. Each Fellowship provided a stipend of $1,000 for a twelve-month period, and the remaining $4,000 was available for operations and publication in conjunction with the usual allotment of funds from the University budget. This grant permitted a considerable extension of the activities of the Station.

During these years space facilities were augmented by the addition of Bagley Hall (1936); the F. K. Kirsten Aeronautical Laboratory (1936); the Civil Engineering Structural Laboratory (1941); and the Civil Engineering building, More Hall (1945-47).

Coming of Age (1948-1961)

The 1947 Legislature allocated $364,714 to the Engineering Experiment Station, which was now responsible for the organization of the expenditure of such subsidies. The allocation provided $277,714 for salaries and wages and $87,000 for operations. The budget, built on the basis of 60 graduate research assistants per year, allowed for substantial additions to the supervising staff. There was also an allowance for the employment of four skilled machinists, the equivalent of three mechanics, and secretarial and stenographic assistance for the director. Out of the total of $87,000 for operations, $75,400 was used in the purchase of much-needed equipment, the largest item being an electron microscope.

In 1948 the *Trend in Engineering,* a quarterly magazine, was begun as an outlet for publicizing the research effort of the College of Engineering, and an able editor was hired for this responsibility. The total number of technical articles appearing in *Trend* since its birth is 237. During this period the Station published 7 bulletins, 2 reports, and 3 volumes covering the Northwest Conference on Road Building.

In the fall of 1960, 2800 students were enrolled; and in June of this year 486 B.S. degrees, 90 M.S. degrees, and 8 Ph.D's were awarded. During these postwar years the Electrical and Mechanical Engineering Buildings were constructed. A graduate program in Nuclear Engineering was established in 1955, and in 1961 the Nuclear Laboratory was dedicated.

The generous grant by the 1947 legislature, which subsidized 60 graduate students per year, did not hold up in succeeding bienniums. The grant was finally stabilized to cover 26 Graduate Research Assistants per year, with a considerably reduced supporting budget. By 1960 the total sum available to the Experiment Station was $127,981 per year. The policy initiated in 1947 has been successful: it has stimulated a growing interest in research and has resulted in a steady increase in Government and industrial support. In 1960-61 the grants from these sources totaled $571,387.

During the current academic year, the large wind tunnel operated by the Aeronautical Department served industry to the extent of $161,840, much of which is available in support of research. Similarly the Structural Research Laboratory earned $6,300 in the same period.

In short, future research in the College has a solid foundation on which to grow.

Chemical Engineering

R. W. MOULTON, *Executive Officer*

The Department of Chemical Engineering has had a program of graduate research of some magnitude for the past forty years. Since World War II this activity has expanded very markedly, and about sixty-five graduate students are now registered in the Department. Of these, about half are candidates for the M.S. degree in chemical engineering, and the other half are candidates for the Ph.D.

The eight permanent members of our faculty have varied educational and industrial backgrounds and interests. The new graduate student is also able to choose his research topic from a broad spectrum of areas of activity. In general, these encompass the fundamental aspects of chemical engineering, but some of the projects are applied and are related to some extent to the interests of the region. For example, research work in progress relates to the pulp and paper industry, the nuclear industry, and the metallurgical industries of this area.

The Chemical Engineering Department has had substantial support from the pulp and paper industry since 1944 in the form of annual grants varying from $20,000 to $60,000. Currently there are active research contracts in the Department supported by the National Science Foundation, the Atomic Energy Commission, the Office of Ordnance Research, the Petroleum Fund of the American Chemical Society, and also separate contracts with some large industrial concerns. This financial support contributes greatly to the graduate research program both in terms of assistantships for students and in supplying funds for the purchase of supplies and equipment.

The following sections illustrate some of the more important typical projects now active in the Department. Space does not permit indicating each of the projects being prosecuted at this time.

Studies Related to Recovery of Reactor-Fuel Elements

During the past five years, the Department of Chemical Engineering has carried out research under contract with AEC upon the chemical-separation processes by which fission products are removed from uranium and plutonium. The recovery of these elements from spent reactor fuel is an aim of the research.

The giant nuclear reactors at Hanford consist essentially of a prism of graphite pierced with aluminum tubes that are filled with slugs of natural uranium jacketed in aluminum. Purified water from the Columbia River is pumped through the annular space between the slugs and the aluminum tubes, to remove the heat generated by nuclear fission. These reactors are used to convert the nonfissionable uranium-238, which is present to the extent of 99.3% in natural uranium, to fissionable plutonium-239. This is accomplished by generating a self-sustaining chain reaction in the fissionable uranium-235, which makes up the remaining 0.7% of natural uranium, in such a way that some of the neutrons produced by fission are absorbed in the uranium-238, converting it to plutonium-239. The by-products of this process, in addition to the fission neutrons, are heat and radioactive fission products, all of which are generated within the uranium slugs. The heat is removed by the cooling water, but the fission products continue to build up in the slugs as long as they are in the reactor.

After the slugs have been in the reactor the required length of time, they are discharged from it and stored in a "swimming pool" prior to being sent to the Separations Plant. At this plant the plutonium and unburned uranium are separated from the fission products, which are subsequently stored in large underground tanks. The plutonium is next separated from the uranium and, after purification and conversion to metallic form, is used in weapons or as fuel for other nuclear reactors. The uranium that has been depleted in the uranium-235 isotope is sent to an Isotope Separation Plant at Oak Ridge, Tennessee. There it is converted to gaseous uranium hexafluoride (UF_6) and forced through metallic "barriers" pierced with microscopic holes. This results in an "enrichment" of the uranium with respect to the uranium-235 isotope. The enriched uranium is reduced to metal, fabricated into fuel slugs, and returned to Hanford or to other sites where natural uranium fuel is required.

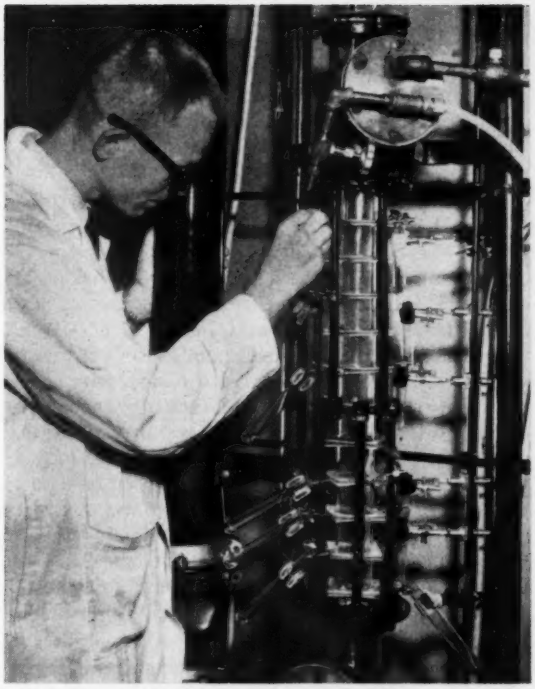
The research carried out in the Department has been concerned with problems of the chemical-separation processes for removing the fission products from uranium and plutonium. The first step in this process involves dissolving the aluminum jackets off the uranium slugs and then dissolving the uranium slug itself in acid solutions. This solution is fed into the center of a tall solvent-extraction tower containing perforated plates. An organic solvent pumped into the bottom of the tower flows upward in the form of small drops countercurrent to the feed stream flowing down the tower. A stream of water containing nitric acid is pumped into the top of the tower, flows down, and mixes with the feed stream. The organic solvent extracts the plutonium and uranium from the feed stream and, when discharged from the top of the tower, is pumped to a second tower in which the plutonium is separated from the uranium. The nitric-acid stream, which tends to keep the fis-

sion products from contaminating the organic stream, is discharged from the bottom of the tower. The entire system is pulsed by means of a bellows actuated by a drive motor.

This system is simulated in our laboratories by using towers 4 in. in diameter, as shown in the photograph. The materials used are not radioactive. The main object of the research to date has been to study factors that affect the efficiency of separation obtained in these extraction towers. These factors include plate spacing, plate materials, plate-hole diameter, pulsing frequency and amplitude, drop size, and stream-flow rates. Many of the studies have been made by using tracers in both the aqueous and organic solvent streams. Other studies have involved the measurement of concentrations existing along the tower during an actual extraction process. Recently, the operation of the tower shown in the photograph was successfully simulated by using an analog computer.

To date, AEC has committed funds totaling $85,000 to this work. In addition, two graduate students have written doctoral theses based on this research work, and one more will complete his work this summer. At the present time, six graduate students working toward M.S. and Ph.D. degrees are working on this project.

A. L. Babb,
Professor of Chemical Engineering



A Section of the Pulsed Solvent-Extraction Column
This equipment is used in studies related to the separation of fission products from uranium and plutonium.

Pulp-Mills Research Program

Seattle has had for the past seventeen years a modest research program dedicated to improved utilization of forest resources by the pulp and paper industry. Seattle is an appropriate location for such a facility, as it is the hub of one of the world's most important regions for the production of pulp and paper. In each direction of the compass are not only forests, but also lumber mills and pulp mills for utilizing these forests in a myriad of products. Seattle also lies in the midst of sports and commercial fishing waters. Though not economically as important as the pulp and paper industry, the fishing and shellfish industries of this region are nevertheless also among the world's largest, and a vital factor in the economy of the Pacific Northwest. The mills are directly concerned with sports and commercial fishing industries, as well as with outdoor-recreation facilities generally, owing to the problems of pollution by mill wastes. With the explosive increase in population, current and expected, ever greater demands will be made upon this region's resources of forest, stream, and living environment.

The pulp-mills research program was established at the University of Washington on January 1, 1944, as a result of a series of conferences among representatives of the pulp and paper industry, the Governor and other representatives of the State government, and the University administrators. The project was to be concerned with more complete utilization of forest growth and with stream improvement. Specifically, the primary emphasis was to be on the effluent streams or waste materials of the pulp mills. The formal agreement made at that time between the University and the pulp and paper industry established three areas in which research was to be carried out: (1) basic research on the chemistry of wood and lignins, (2) utilization of pulp- and paper-mill wastes in industry and trade, and (3) sanitary-engineering and sewage-disposal methods for pulp- and paper-mill wastes.

The program was established to carry out these objectives, with three University areas involved. Basic chemical research was conducted by Dr. D. M. Ritter and associates in the Department of Chemistry,

and utilization research by Professor W. L. Beuschlein, Dr. Joseph L. McCarthy, and associates in the Chemical Engineering Department (then part of a joint chemistry-chemical engineering department). Sanitary engineering and disposal methods were carried out by Professor R. G. Tyler and associates in the Department of Civil Engineering.

After a period of about five years, the research had developed into a pattern emphasizing lignin chemistry and the chemical engineering or processing type of problems. The three administrative divisions became one, and since that time the program has been mainly under the direction of Joseph L. McCarthy, now Dean of the Graduate School of the University. In 1960 a fourth research area was added by agreement between University and industry representatives, to the existing three—basic research, utilization of wastes, and disposal. Thus included is study of the relationship of pulp-mill wastes to other uses of water, to fish and aquatic life, and to water quality in general. Joining the research group in this area of interest in 1960 was Dr. Lauren Donaldson of the College of Fisheries. The specific research area supported in this program is the selective breeding of Chinook salmon.

The overall program since its inception has been administered through a Pulp Mills Research Committee under the direction of the Dean of the Graduate School. Members of this committee have typically been drawn from forestry, chemical engineering, chemistry, civil engineering, and microbiology. The pulp and paper industry is kept informed of activities through a committee of representatives, one from each industrial member. In recent years these industrial members have belonged to the Northwest Pulp and Paper Association, with Mr. Vinton W. Bacon, Executive Secretary for that organization. Although industrial sponsorship has changed from time to time, current support of the program comes from Cascade Kraft Corp., Columbia River Paper Corp., Coos Bay Pulp Corp., Crown Zellerbach Corp., Fibreboard Paper Products Corp., Inland Empire Paper Co., Longview Fibre Co., Pacific Pulp Molding Co., Publishers Paper Co., Puget Sound Pulp and Timber Co., Rayonier, Inc., Scott Paper Co., Simpson Paper Co., St. Regis Paper Co., West Tacoma Newsprint Co., Western Kraft Corp., and Weyerhaeuser Timber Co.

Meetings are held semiannually, or sometimes more frequently, among those responsible for the research program at the University, the University Pulp Mills Research Committee, and the Northwest Pulp and Paper Association. Written reports are transmitted and discussed at this time.

Since its inception in 1944 the Pulp Mills Research program has been guided by several long-term objectives. The initial impetus to the program stemming from an interest of both the State and industry in improved forest utilization and stream quality has continued to be an important factor in guiding research. The position of the University as an institution intended to serve the State, conduct research, and prepare young citizens for useful contributions to their community during their careers has also influenced the nature of the projects investigated. Many of the students who have participated in the program are now making responsible contributions within the pulp and paper industry of the Northwest and elsewhere. Contributions to the basic knowledge of forest products and their utilization have been made permanently and generally available through presentation at meetings and publications in technical periodicals of world-wide circulation. In many instances, it has been found possible and indeed desirable to fulfill each of these objectives, as can be shown by reference to numerous contributions to the *Journal of the American Chemical Society, Journal of the Technical Association of the Pulp and Paper Industry,* and other appropriate periodicals. A description of some 60 such contributions and also a summary of the Pulp Mills Research Program through the summer of 1957 may be found in a paper by Vincent F. Felicetta and Joseph L. McCarthy.* A recent General Report to the University Pulp Mills Research Committee** listed 66 students and part-time personnel who have contributed to and benefited financially from this research program. An enumeration of the papers discussed in the Technical Section of the same report may indicate the kind of work currently being conducted in the Pulp Mills Research Program (See Table I). Some of the topics are continuing or revitalized, and not all receive equal emphasis in the program.

The original agreement provided financial support by the industry of $50,000 to $60,000 per year to maintain the research. This continued until 1950, at which time the funds granted were reduced to $20,000 annually, with only sulphite pulp mills continuing to support the research. In 1956 the support was again broadened to include Kraft mills, and financing was increased to a level between the above extremes, where it remains currently. To date, the cumulative total expenditures have exceeded $600,000. By far the largest items of expenditure have been the financial aid of graduate students by means of research assistantships and salaries of professional personnel.

The long-term goals of the Pulp Mills Research Program can perhaps be better described if specific topics such as those in Table I are related to the paper- and pulp-making processes. Chemical wood

* TAPPI, Vol. 40, No. 11 (Nov., 1957), p. 851.
** *Report XXXIX,* General Section (Dec. 1, 1960).

TABLE I

TITLES OF RESEARCH TOPICS REPORTED IN PULP MILLS RESEARCH GENERAL REPORT

TOPIC	TITLE OF RESEARCH	INVESTIGATOR
A	Characterization of Lignin by Nuclear Magnetic Resonance	C. H. Ludwig
B	Hydrogenolysis of Lignin Sulfonates	B. F. Hrutfiord
C	Lignin Cleavage by Gamma Radiation	R. S. Gaudette
D	Low Molecular Weight Lignin Sulfonates	S. W. Schubert
E	Studies of the Cellulose-Water System	N. T. Anderson
F	The Pearl-Benson Method for the Estimation of Spent Sulfite Liquor Concentration	V. F. Felicetta J. L. McCarthy
G	The Statement of a Tentative Standard Pearl-Benson or Nitroso Method	V. F. Felicetta J. L. McCarthy
H	A Preliminary Study of the Possibly Unique Determination of Lignin Sulfonates in Water	V. F. Felicetta J. L. McCarthy
I	Volatile Components in Spent Sulfite Liquor	B. F. Hrutfiord
J	Sulfur Dioxide-Ammonia-Water Equilibrium	W. D. Scott
K	Sulfur Dioxide Absorption Tower Design	D. Ratkowsky
L	Characterization of Kraft Blow Gas Condensate Oil	B. F. Hrutfiord
M	Steam Stripping of Volatile and Odorous Substances from Kraft Pulp Mill Aqueous Streams	M. J. Matteson L. N. Johanson J. L. McCarthy
N	Vapor-Liquid Equilibrium of Water-Sulfide Systems	R. S. Gaudette
O	Full-Scale Stripping-Column Design Study	H. Maahs L. N. Johanson
P	Venturi-Scrubber Design Studies	J. A. Gieseke
Q	Analysis of Aqueous Samples by Gas Chromatography	B. F. Hrutfiord
R	Selective Breeding of Salmon	R. Donaldson

pulp is essentially the cellulose remaining as fibers after chemical reaction and removal of the other constituents, mainly lignin and hemicelluloses. The pulp, which consists of about one half of the original woody tissue, may be further processed into paper of various types, paper-board products, or into dissolving cellulose for further manufacture. The University Pulp Mills Research program has not emphasized these pulp-converting processes, and has considered the pulping process itself only insofar as it relates to improved utilization or recovery of heat and chemicals. The chemical removal of non-cellulose constituents may be broadly divided into "Kraft" and "sulfite" processes as conducted in the Pacific Northwest.

The Kraft process utilizes sodium hydroxide and sodium sulfide in water solution to dissolve and remove the lignin as "black liquor." This is concentrated by repeated (multiple-effect) evaporation and eventually burned in a "recovery furnace," to recover most of the original dissolving chemicals and also substantial quantities of heat as steam. This process during its industrial development has been greatly improved with respect to the utilization of the non-cellulose constituents of wood as recovered energy. It has also decreased the problems arising in connection with disposal of the dissolved lignins. However, problems still remain with respect to odorous substances arising from the nature of the process. These substances can unfortunately be detected by the human nose in extremely low concentrations, so that even 99% containment and recovery is insufficient. Topics L, M, N, O, and Q of Table I are part of a program intended to help minimize this odor problem, particularly with respect to the dilute aqueous streams of Kraft pulp mills. Topic P is closely related, but is concerned with the methods of design of suitable systems for "scrubbing" the stack gases of the recovery furnaces for improved recovery of heat

DR. HRUTFIORD AND DR. JOHANSON
DISCUSS A CHROMATOGRAPHIC ANALYSIS

and chemicals and for improved control of odorous effluents.

There is a greater variety of sulfite than of Kraft processes. Wood is chemically treated with a solution of sulfurous acid and a metal sulfite in water. Calcium, magnesium, sodium, or ammonium sulfites may be used, each having specific advantages with respect to wood species usable, pulp quality, chemical recovery, and costs. In general, disposal of the lignin-containing "liquor" is more of a problem than with Kraft processes. Topics F, G, H, and I are concerned with the important problem of specifically detecting and quantitatively estimating chemical constituents of "sulfite spent liquor" in extremely dilute concentrations in fresh and salt waters. Topics J and K are associated with the chemical-recovery processes that are generally applicable to all of the sulfite processes.

Topic R relates to the recently defined objective of the Pulp Mills Research Program of relating pulp-mill wastes to other uses of water, to fish and aquatic life, and to water quality in general.

Throughout the scientific revolution it has been almost an axiom that the greatest progress is made in practical, applied problems if they are well supported by a foundation of basic or fundamental research. This is also true in the pulp and paper industry, as was recognized at the time of the 1944 pulp-mills research agreement by provision for such research. Topics A, B, C, and D are thus concerned with the basic chemistry and structure of lignins, and topic E with the structure of cellulose, which is important for improved knowledge of its properties in woody tissues and derived products.

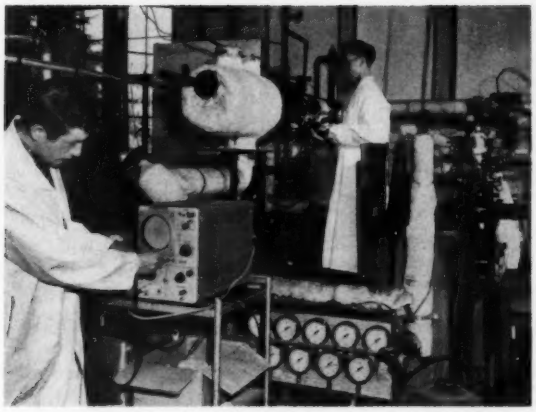
The research emphasis varies from year to year, as problems of importance change. Evidence indicates that the general goals of the Pulp Mills Research Program have continued to be met since its inception in 1944. The direct goals may be paraphrased as research toward (1) improved knowledge of the chemistry of lignins and other wood constituents, (2) improved utilization of these constituents, (3) minimizing the contamination of air and water environments, and (4) improved understanding of the relationship of pulp and paper mills to water quality and aquatic life. However, the indirect benefits, which are also important, include (1) provision of a forum of industrial representatives for discussion and research toward a common solution of their problems, (2) financial support of graduate-student research, and (3) development of a source of talent for employment in the Northwest pulp and paper industry.

L. N. JOHANSON,
Associate Professor of Chemical Engineering

Critical-Flow Studies

One of the research projects that have received considerable attention in the Department of Chemical Engineering at the University of Washington over the past five years is called critical flow. When a fluid passes through a pipe or other duct under the influence of extremely high driving forces under certain conditions, it will reach the velocity of sound, where a choking or self-limiting effect often occurs. This phenomenon, which is especially pronounced for two-phase mixtures such as water and steam or a liquid and an inert gas, has been recognized for some fifty years; but only recently have engineers and scientists been concerned with the theoretical basis for this type of flow limitation.

With the discovery of the fission process and the subsequent development of the atomic bomb and nuclear power plants, much interest has been centered on the atomic-energy industry. The peacetime uses of atomic energy are many and varied, but the major emphasis certainly has to do with the production of power in such a way that it can compete with other types of fuel. A great expenditure of effort by engineers in this and other countries has resulted in the development of many different kinds of nuclear power



TAKING DATA ON THE FLOW OF A STEAM-WATER MIXTURE

plants. In order to achieve a moderate degree of efficiency, temperature levels must be kept as high as possible. In addition to operation at substantially high temperature levels in the core of the nuclear power plant, the removal of heat from the nuclear fuel elements must be accomplished in a carefully controlled and efficient manner. Many ways have been developed for doing this, including gas and liquid cooling and other techniques. Perhaps the most widely used method of heat transfer is the use of a circulating fluid.

Many heat-transfer agents have been tried and are being used for the transfer of heat from the nuclear fuel assembly to other parts of the nuclear power plant. A fluid that has good nuclear as well as good thermal and physical properties is ordinary water. In order to operate effectively at the temperatures desired, the circulating water system must be maintained under a rather high pressure. Pressures utilized in this industry are today in the order of one to five thousand pounds per square inch.

A nuclear power plant represents a certain hazard. Every possible precaution is taken to make the plant safe and to prevent any catastrophic runaway that would result in injury to personnel or damage to property. In operating a water system at high temperatures and pressures, there is always the possibility of a failure in the circulating-water system. When the water is close to or at its boiling point, a rupture in the system will necessarily lower the pressure and result in vaporization of the water. The material then discharging from the point of rupture is a mixture of water and steam. Under this type of flow condition, there is almost a certainty that critical flow rates will control the rate of blow-down of the system.

In the emergency shutdown of a nuclear reactor, all possible combinations of circumstances must be considered. Depending upon the design of a nuclear reactor, the loss of the coolant may cause the reactor to operate at either a higher or a lower power level. If the loss of the coolant results in operation at a higher power level, the situation introduces an additional hazard into the reactor operation. It becomes extremely important to know the degree of this increase in power level, as safety devices have to be designed to cope with the situation. For these reasons engineers who design nuclear reactors are concerned with study of critical-flow rates.

In 1956 a program of research was started in the Department, in an effort to study on a more theoretical basis the phenomena of critical flow. Theoretical mathematical studies of these phenomena indicated that the maximum flow to be realized under critical-flow conditions would be related to the compressibility of the two-phase mixture and would also be exactly equal to the acoustic velocity in the two-phase mixture. The theoretical derivation for acoustic velocity in a homogeneous medium is also a function of the compressibility of the medium and, of course, is equal to the velocity noted above. Work reported in various laboratories in this and other countries indicated that the actual measured flow rates under critical-flow conditions exceeded the theoretical flow rates, especially at low qualities for steam-water mixtures. This significant deviation in some instances was as much as two to five times the theoretical value. This is far too great a deviation to be explained by errors in the recording or measuring of data.

Two important considerations all investigators were aware of, but which none had particularly evaluated were (1) slip between the two phases and (2) a departure from thermodynamic equilibrium. Force-balance considerations indicate that the acceleration of the less dense medium, usually the vapor phase, will be greater than that of the liquid phase. If the vapor phase is traveling at a higher velocity than the liquid phase, then less cross-sectional area is required to accommodate the volumetric vapor rate; and this significantly alters the flow characteristics. The end result is that a greater mass-flow rate will result than if the two phases were moving at the same velocity.

A complicating factor in two-phase flow is that the physical distribution of liquid and vapor between the two phases will be altered significantly, depending upon the velocity, the ratio of vapor to liquid, the slope of the duct in which flow is occurring, and other factors. Various investigators have reported slug flow, annular flow, fog flow, wave-like flow, frothing flow, and others.

If there is slip between the vapor and liquid phases so that the vapor phase moves at a greater lineal velocity than the liquid phase, it will serve to explain in whole or in part the deviation of the observed ex-

perimental results from the theoretical values. One way to measure the slip between the two phases is to determine the momentum of the moving mixture. Research work is now under way at the University to evaluate this aspect of the problem.

In a flowing two-phase mixture wherein the absolute pressure is dropping rapidly, vaporization will be simultaneously occurring. In order for the liquid to vaporize, heat must be supplied to the vaporization zone. This heat will necessarily come from the sensible heat content of the liquid. Therefore the liquid will cool in the vaporization process, the result being a lowering of temperature and pressure in the direction of flow. Most investigators have felt that the temperature and pressure for a water-steam mixture would be related by known saturation conditions and could be determined readily from reference to standard steam tables.

Under conditions of normal flow, vaporization of the liquid phase and simultaneous cooling would occur with great speed, the result being very little departure from equilibrium. Under conditions of critical flow, however, the flow rates are so high as to make it certainly conceivable that insufficient time would elapse over a given section of pipe length for the heat to be transferred from the bulk of the liquid to the vaporization zone, so that there would be some small but finite superheating of the liquid because of this delay in heat transfer. Any departure from thermodynamic equilibrium in this direction would result in a lower average specific volume than would otherwise be the case; and as a result the observed flow rates would be significantly higher than those predicted from theory. This facet of the problem is also being investigated at the University.

In the spring of 1960, funds were obtained from AEC in the form of a research contract for the support of this program. At the present time, two doctorate candidates are working in this area. One of these men is studying the problem of relative velocity of the two phases; the other, the departure from thermodynamic equilibrium. Within the next twelve months, data forthcoming from this work should assist in elucidating this important problem.

R. W. MOULTON,
Professor of Chemical Engineering

Nuclear Engineering

A. L. BABB, *Chairman, Nuclear Engineering Committee*

The nation-wide shortage of engineers has been particularly apparent in the field of nuclear energy, where the need is increasing for men qualified to assist with the planning, design, development, and operation of processes and systems involving nuclear transformations. The applications and potential applications in stationary and mobile power units—particularly nuclear-propelled ships, chemical processing, instrumentation, and industrial operations such as radiography and thickness gauging—have increased enormously in the past few years, and the signs indicate even more rapid increases in the immediate future.

In recognition of the need for trained men in this field, the College of Engineering inaugurated five years ago a graduate-study program in nuclear engineering leading toward a M.S. degree. This program is a cooperative effort of the Departments of Chemical, Civil, Electrical, Mechanical, and Metallurgical Engineering. The program is administered by a college-wide committee composed of representatives of these departments, with the chairman of the committee reporting to the Dean of the College of Engineering. Doctorate programs with nuclear engineering as the minor field are now offered by several cooperating departments.

FACILITIES

After the Atomic Energy Commission initiated its educational-aid program in the fall of 1956, the University received grants to equip six special laboratories for teaching and research in nuclear engineering: nuclear metallurgy, radioactive wastes, radiochemistry, nuclear instrumentation, radioactive tracers, and nuclear engineering. A seventh laboratory containing both boiling-water and liquid-metal heat-transfer loops, has just been set up in the Mechanical Engineering Building.

The natural uranium-graphite subcritical reactor, shown in the first photograph, was constructed for use in the nuclear-engineering laboratory. There is also a small analog computer, which is used in the nuclear-engineering and nuclear-instrumentation laboratories to simulate the time behavior of nuclear-reactor systems. In addition, the IBM 650 and 709 digital computers, located temporarily in the Mechanical Engineering Building, are used by students in calculations involving the subcritical reactor and in graduate courses in reactor design.

On April 10, 1961, the University of Washington Nuclear Reactor was placed in operation, so becoming the focal point for the new Nuclear Reactor Laboratory Building designed specially for this facility (see picture on cover).

The lower part of this building is embedded in a sloping bank; the upper part is framed in aluminum, glass, and reinforced concrete. The main laboratory

and operating console room are completely visible from the outside plaza on the upper level. The natural slope of the site, west to east, permits the location of the reactor itself below grade. A radiochemistry laboratory and counting room open directly onto the main floor of the reactor room, which is 70 ft wide and 48 ft long. The control room and briefing room on the upper level at the east are separated from the reactor room by a glass-curtain wall. Sliding glass doors permit direct view and access to the control room from the briefing room for lecture-demonstrations. Offices, shops, and study areas are provided on the lower level at the east, separated from the reactor room by a 6-in. reinforced concrete wall.

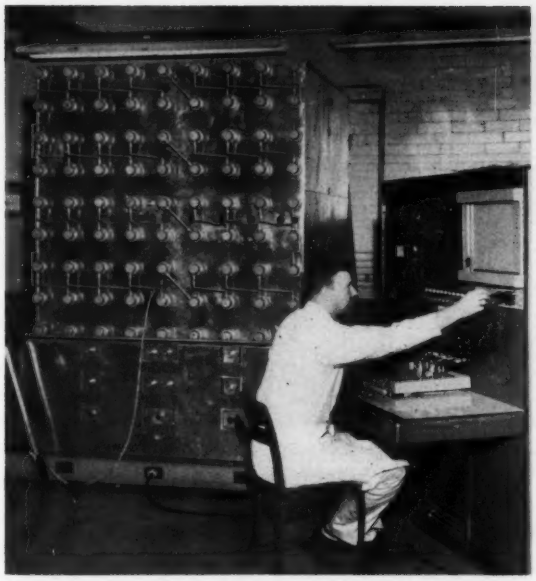
RESEARCH PROGRAMS

A variety of research programs are available from which students may select thesis topics. These include studies involving two-phase flow, boiling-heat transfer, ion-exchange separations, solvent extraction, engine-wear problems, radiation dosimetry, waste-disposal problems, metallurgy of reactor materials, reactor-physics lattice constants, instrumentation, effect of gamma radiation on chemical reactions and materials, and radiochemical separations. Several of these topics are described briefly in the following sections.

Predicting the Properties of a Critical Reactor

One of the facilities available for education and research in nuclear engineering is the subcritical natural-uranium-graphite reactor. This reactor, acquired in 1957, consists of a lattice of cylindrical natural-uranium fuel elements positioned in an approximately cubical matrix of graphite. The Hanford-type fuel elements are located in channels through which a fluid may be circulated for controlling temperature. To maintain a neutron population within the subcritical reactor assembly, one to four Pu-Be one-curie fast-neutron sources located in the graphite supporting pedestal are used. The exposed surfaces of the system are covered with cadmium sheeting sandwiched between aluminum.

The experimental variable of primary interest is the neutron density or flux, and instrumentation for its measurement is available. A sufficient number of channels exist within the graphite matrix for these measurements so that a complete mapping of flux as a function of position may be obtained. The system is truly versatile, inasmuch as source position, reactor temperature, and type of reactor coolant may all be varied, and their effect on the flux distribution determined.



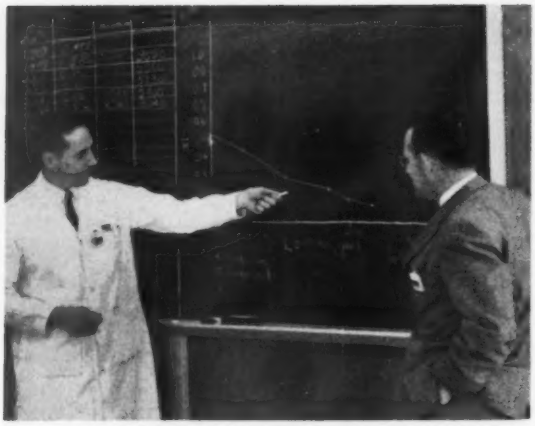
THE NATURAL URANIUM-GRAPHITE SUBCRITICAL REACTOR

The reactor is used primarily for teaching, and serves as a basis for introducing engineers to the problems associated with the nuclear chain reaction. The experimental measurement of quantities enables students to acquire an appreciation for the significance and meaning of nuclear parameters and of the limitations of reactor theory that study alone could not. To these ends the subcritical reactor is ideally suited since almost all of the steady-state reactor-physics experiments performed on a critical pile can also be performed on a pile of this type, but at far less expense and with little hazard.

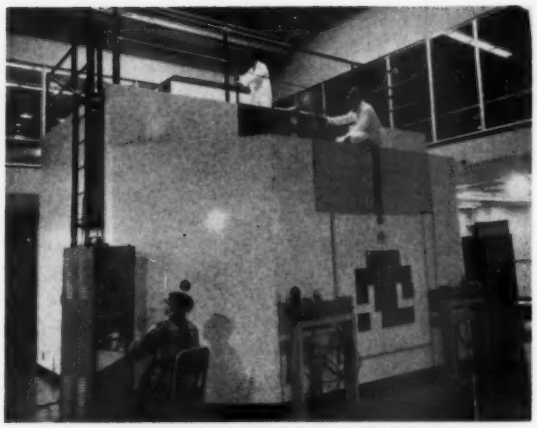
Use of the subcritical reactor, however, is not confined to classroom purposes. By using experimental neutron-flux data and an IBM 650 high-speed computer, accurate determinations have been made of such parameters as material buckling, diffusion length, and effective size. To predict these theoretically for a heterogeneous system is a job characterized by difficulties and uncertainties.

A study currently under way is that of determining the effect of a change in temperature on the lattice constants. This also is very difficult to predict theoretically, but can be measured experimentally if the temperature of the pile can be varied. The information so obtained may be used in estimating the temperature coefficient of reactivity, a vital parameter in calculating the controllability of any reactor system.

A project that utilizes a promising new technique is the use of a pulsed source of neutrons rather than the steady sources now in use. Such sources supply



PROFESSORS MCFERON AND MOULTON
FOLLOWING THE INITIAL APPROACH
OF THE NUCLEAR REACTOR TO CRITICALITY



FRONT VIEW OF THE NUCLEAR REACTOR
The removable shield blocks and the access plugs in Block I lead to the graphite thermal column; the two control-rod drive assemblies are shown on the left and right of the front face.

high-intensity bursts of neutrons for very short (microsecond) time intervals. In using the method to obtain lattice parameters, the neutron population is measured as a function of time and position, and these data are compared with the transient diffusion equations. A wide variety of parameters may be obtained more quickly and accurately than with conventional methods.

K. L. GARLID,
Assistant Professor of Chemical Engineering

Reactor Dynamic Studies

The ultimate purpose in constructing a nuclear power reactor is to provide a useful source of energy. Consequently, for a nuclear power reactor to be of practical use, some means of controlling this energy source must be provided. In a conventional energy source—for example, an oil-fired furnace—the rate of energy production is controlled by controlling the rate of fuel delivery to the system. The amount of fuel contained within the active-energy production portion of the system is very small compared to the fuel-consumption rate. Under these conditions the rate of energy production is proportional to the rate of fuel delivery. However, in a nuclear reactor, the amount of fuel, fissionable material, contained within the reactor is enormous compared to the fuel-consumption rate. Thus a nuclear reactor cannot be controlled by controlling the rate of delivery of fissionable material to the reactor. Control can be obtained only by directly controlling the fission chain-reaction process that occurs within the reactor. Thus a nuclear reactor is, in general, a much more difficult type of energy source to control than a conventional one. Any mechanism that affects the chain-reaction process will, in turn, affect the control aspects of a nuclear reactor.

The ultimate controllability of a nuclear reactor is primarily dependent upon the fact that the neutrons emitted in the fission process are not all emitted instantaneously. A very small fraction of the fission-produced neutrons called "delayed neutrons" are emitted by unstable fission-product atoms at discrete times after the fissioning of a fuel atom occurs. In a Uranium-235 fueled nuclear reactor these delayed neutrons comprise only some 0.64% of the total number of fission neutrons produced. This small but very important fraction of the total number of fission-produced neutrons governs the kinetic behavior of a nuclear reactor and makes reactor control possible.

One of the dynamic-analysis methods currently being investigated for use of the University of Washington Teaching Reactor is called the "Pile Oscillation Technique." This involves treating a nuclear reactor as a "neutron amplifier." The conventional technique of frequency-response analysis may then be applied to obtain information about the kinetic and dynamic response of a reactor. That is, analogous to the method employed for testing electronic amplifiers, the reactor's response to a sinusoidally varying input is observed. The device used to produce the sinusoidally varying input is appropriately termed a "pile oscillator." The reactor's response to the pile oscillator is observed in terms of phase angle and gain characteristics. These observations yield data for plotting the transfer-characteristic curve of the reactor, which in turn may be utilized to compute such fundamental reactor parameters as the effective fraction of delayed neutrons.

W. E. WILSON, JR.,
Associate Nuclear-Reactor Engineer

Long-Term Effects in Reactors

During the course of their lifetime, the components of a nuclear power reactor undergo many changes. These are caused by the radiative environment in which the various parts must operate as well as by the more conventional effects of temperature, pressure, and contacting substances. Some of the changes affect the operating characteristics, including safety, and almost all variations will affect the economy of operating large nuclear-power stations.

Since the economic and safety incentives are large and the amount of actual operating experiences is small at this time, a considerable amount of engineering effort is currently being expended in the solution of some of these problems. Starting with some of the experience and using information derived from low-power reactor tests, the nuclear engineer extrapolates these data based upon developed theory. The phenomena involved being relatively complex, he resorts to large digital computers in seeking the solutions to many of these problems.

As an example of some of the kinds of problems we mean, let us consider the elementary reactions taking place in the fuel of a reactor that uses uranium as fuel. Natural uranium is composed essentially of two isotopes, U-235 and U-238. In the usual nuclear reactor only the U-235 isotope fissions and thus sustains the chain reaction; however, the U-238 isotopes can capture a neutron and be converted into the fissionable isotope Pu-239. The reactions are given below:

$$_{92}U^{235} + {}_{0}n^{1} \rightarrow {}_{92}U^{236} \rightarrow F.P. + 2(\text{or } 3)\,{}_{0}n^{1}$$

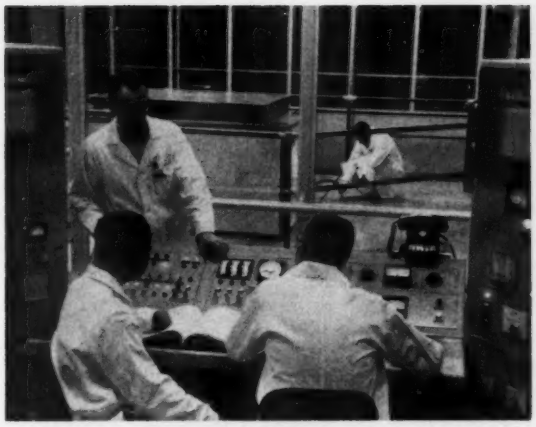
where $_{0}n^{1}$ represents a neutron and *F. P.* represents the fission products formed. The fission products formed in this reaction include all of the elements in the periodic table from zinc to the rare-earth element, terbium. Not all of these elements are useful or desirable in the fuel element, and almost all are radioactive and in turn decay to still other elements. In U-238 the important reaction is as follows:

$$_{92}U^{238} + {}_{0}n^{1} \rightarrow {}_{92}U^{239} \rightarrow {}_{93}Np^{239} + {}_{-1}e^{0}$$

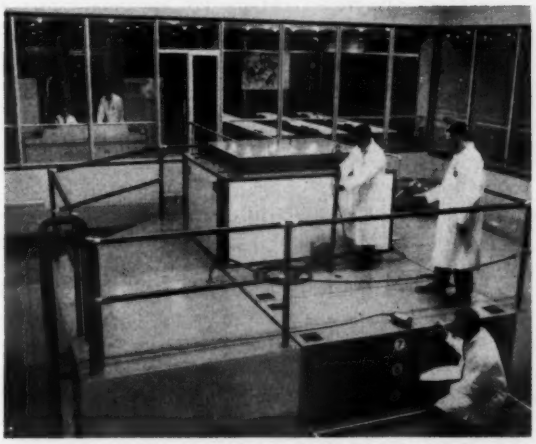
and

$$_{93}Np^{239} \rightarrow {}_{94}Pu^{239} + {}_{-1}e^{0},$$

where Np is the element neptumium, $_{-1}e^{0}$ is a beta particle given off, and Pu is the element plutonium. Since Pu-239 is also a fissionable isotope, the conversion of the U-238 to plutonium results in the transformation of a non-usable fuel into a usable type. These reactions are only a small sample of the large number of changes that take place not only in the fuel but also of the somewhat similar ones that occur in the structural components and coolants throughout the lifetime of the reactor.



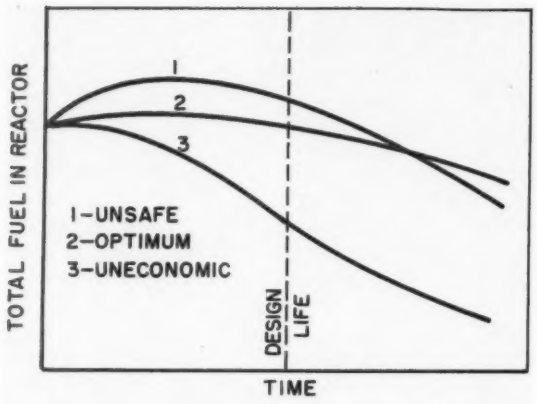
PROFESSOR A. L. BABB, REACTOR SUPERVISOR, INSTRUCTING GRADUATE STUDENTS ON THE USE OF INSTRUMENTS FOR REGULATION AND OPERATION OF THE NUCLEAR REACTOR



INSERTING A NUCLEAR COUNTER INTO THE TEST HOLE ATOP THE REACTOR

Radiation monitors keep the operation under surveillance. The reactor is seen from the upper balcony: the control room is at the left, rear, and the briefing room at the right.

In the case of changes in the fuel composition during the course of reactor operation, a number of effects have been noted or predicted. One of the first of these has to do with the useful lifetime of a particular loading of fuel. Since some of the fuel is being used up at the same time that new fuel is being generated, the relative rates of these two processes determine the fuel available at any particular time. It is important to the safety and economy of the opera-



FUEL CHANGES IN NUCLEAR REACTOR OPERATION

tion that the fuel inventory not rise above a certain limit or fall below a given limit during the useful life of the fuel. As illustrated in the figure on this page these limits are rather narrow for the most efficient utilization of the fuel.

Another somewhat related problem has been studied recently.* This study was directed at the effect of the change in fuel composition over long periods of time upon the safety aspects of reactor operation. The plutonium, which forms in the burning of low enrichment (small percentages of U-235) uranium fuels, has quite different nuclear characteristics from that which it replaces. The long-range effect of these changes is to cause the control of the reactor to be slightly more sensitive toward the end of the fuel lifetime than at the beginning. This indicates that the original design of the system used to control the reactor should be designed with this criteria in mind, a factor which could influence the safety of the power plant as well as the economy of operation.

Other similar studies to be carried out in the future have to do with the effect of changes in the type and arrangement of the fuel so as to optimize the reactor from the standpoint of economy while it operates within the necessary boundaries of safety. These studies are a natural consequence of the development of the nuclear-power industry to the point where engineering optimization based upon the existing background of reactor technology and theory is the next logical step in the design of power plants.

D. E. McFERON,
Professor of Mechanical Engineering

*C. W. Savery, Jr., "Reactivity Effects of Fuel Burnup in Nuclear Reactors," M.S. Thesis, University of Washington, 1960.

Radiation Shielding for Mobile Power Plants

In most stationary reactors built to date, the shielding designer has had little restriction in providing the required radiation attenuation. In mobile nuclear power plants for submarines, surface ships, and aircraft, however, it is absolutely essential to minimize the weight and volume of the reactor shield. In fact, in aircraft propulsion the weight of the shield has overriding importance. If the shielding is too heavy, the reactor may prove to be unsatisfactory for the intended purpose. Moreover, in nuclear ship propulsion, the primary objectives are to reduce cost and to reduce the weight-to-horsepower ratio.

A better understanding of the mechanism whereby neutron and gamma radiations are attenuated for various source-shield geometries will permit the calculation of shield thicknesses to closer tolerances and consequently will tend to reduce the shield weight. For example, the power plant for the first nuclear-powered merchant ship, N. S. *Savannah,* has a gross weight of 3650 tons, of which 1600 tons is attributable to the weight of shielding materials. Thus the shielding, which makes up about 44% of the gross weight of the power plant, greatly increases the weight-to-horsepower ratio over and above that for conventional ships.

In addition, a thorough study of materials presently available and of new materials suitable for neutron and gamma shields will provide information necessary for increasing the shield efficiency per unit weight and reducing the cost of installation. For example, in nuclear-powered ships lead is cast in thick slabs and then welded to the bulkheads to provide both primary and secondary gamma shields. The joints between the shields are welded by hand at a rate of 3 to 5 in. per day. A nuclear-powered surface vessel now under construction at Bethlehem Steel's Quincy, Massachusetts, shipyard has four vertical seams 30 to 35 ft. high, plus horizontal seams, in each reactor-compartment bulkhead.

The particular research program now being conducted includes (1) the investigation of the fundamental mechanisms of radiation attenuation for various source-shield geometries and (2) a study of various pure materials suitable for neutron and gamma shields with a view to developing a low-cost, easily applicable, highly efficient, composite shield to meet the requirements of mobile nuclear-propulsion systems. The experimental phases of both areas involve the use of the University of Washington Nuclear Reactor.

A. L. BABB,
Professor of Chemical Engineering

Electrical Engineering

A. V. EASTMAN, *Executive Officer*

The Department of Electrical Engineering has experienced what can truly be called an explosive increase in research during the past five years. The volume of contracted research, which now stands at $300,000 per year, has more than doubled during the past two years. A large number of proposals for new research are currently outstanding, and quite possibly the volume will again double during the next two years. Such a rapid increase in research efforts has been made necessary by the correspondingly rapid increase in the graduate enrollment, which has accompanied the introduction of a large-scale Ph.D. program.

The major technical fields in which research programs are in effect in the Department are electro-magnetics, solid-state electronics, control systems, digital computers, and information theory. Additional fields where future research support is anticipated are microwave electronics and plasma electronics. In the articles to follow, selected details are given about most of the research projects now in progress within the Department.

ANTENNA LABORATORY RESEARCH

The antenna research of the departmental Antenna Laboratories is divided into three basic divisions: (1) Microwave Antenna Synthesis, (2) Traveling Wave Antennas, and (3) Statistical Aspects of Antennas. Each of these divisions has several projects under investigation by masters and doctoral candidates. The following sections summarize some aspects of each of these divisions.

Microwave Antenna Synthesis

In recent years, considerable attention has been given to the study of flush-mounted microwave antennas because of their inherent adaptability to high-speed aircraft, missiles, and rockets. These antennas often take the form of aperatures or slots in the metallic surface of aircraft.

The Department is engaged in research aimed at the synthesis of flush-mounted microwave antennas to produce a prescribed radiation pattern. For this purpose, the relationship between the radiation pattern and the aperture or source fields must be established, and the capacity of the surface to utilize such aperture fields must be investigated. In achieving this broad objective, the research efforts are separated into the following branches, each of which is pursued by graduate students:

Modulated Antennas. If such characteristics of the surface as impedance and shape are modulated or varied along the surface, the amplitude and the phase of the guided wave are modulated as a function of distance. The result is a new type of antenna: its characteristics can be varied as the various parameters are varied. The radiation pattern from such a modulated surface has been ordinarily expressed in an infinite-series form, but a new method of analysis using a closed form has been under study. In connection with this work, there is an urgent need for the tabulation of Anger and Lommel-Weber functions because the present tables of these functions are incomplete. They are to be completed in the near future. This work is being done under Air Force contract.

Frequency-Scanning Antennas. When the periodic structure is excited by a slow wave structure, the resulting radiation characteristic shows strong dependence on frequency. This point of view was further investigated for linear and Tchebyscheff arrays to yield a 180° scanning.

Azimuthal Radiation Pattern Synthesis. Often there is a practical need for beam shaping in the azimuthal direction, to include the cardioid and the Tchebyscheff patterns. The circular aperture-type antenna has been studied in the hope of producing such a pattern, and a report is being prepared. This work, which is being done under AF contract, is now being extended to the study of a circular cylinder.

Corrugated Slow Waveguide. To excite the surface-wave antenna or the modulated antenna, a slow waveguide must be obtained. A rectangular waveguide containing corrugation is being studied both theoretically and experimentally.

Waveguide Filled with an Anisotropic Medium. The rectangular waveguide filled with anisotropic materials such as ferrite with the d-c magnetic field in an arbitrary direction presents an extremely difficult boundary-value problem. It is attacked by means of the eigenfunction in one direction and the series in the other, the result being complex matrix and determinant problems. These are now being studied.

Slow and Leaky Waves. When a periodic structure supports a wave, there is a region of the parameters in which all the space harmonics are slow; but sometimes a part of the harmonics are in a leaky region. This is ordinarily called a "Forbidden Region" because of its attenuation; but this attenuation is in fact useful for its radiation in various directions. This little-understood region is being investigated.

Periodically Apertured Screen. The study of a periodically apertured screen is interesting because of its practical application to aircraft radomes and its theoretical significance in terms of its periodic char-

acteristics. Dr. R. B. Kieburtz, now an assistant professor at New York University, and the author have attacked this problem by means of variational principles and also by means of the integral-equation formulation.

Surface Currents on a Curved Surface. Surface currents excited by a slot on a curved surface are a particularly interesting problem because they furnish the coupling between series of the slots on a curved surface. This problem has been attacked by means of the residue series and the airy integral-approximation techniques.

A. ISHIMARU,
Associate Professor of Electrical Engineering

Research in Long Traveling-Wave Antennas

In radio communications, radar, and radio astronomy, the antenna is indispensable. In these fields there has been a constant demand for antennas of ever-increasing size and complexity. Typical examples are a parabolic reflector antenna 600 ft. in diameter currently being installed by the Navy in West Virginia, a two-mile-long radio-astronomy antenna in Southern California, and the giant antenna system stretched between two ridges of the Cascade mountains at Jim Creek, Washington.

The Department is engaged in an investigation of the properties of a class of antennas, potentially very big ones.* These are the so-called traveling-wave antennas that use structures with relatively small cross-sectional area, but great length, which may be traded for area in the following way: A square-aperture antenna (such as a horn or a parabolic reflector) D wavelengths on a side will have about the same maximum directivity as a traveling-wave antenna D^2 wavelengths long. Thus, at a frequency of 300 Mc, where the wavelength is 1 meter, a parabolic reflector antenna 15 meters in diameter (about 50 ft) will have very nearly the same performance as a traveling-wave antenna 225 meters long (740 ft). For some applications, particularly those in which the antenna is to be directed in a fixed direction tangent to the earth, as it is for point-to-point communications, the long antenna can be mounted inexpensively on simple posts, and may well be considerably cheaper than the aperture antenna.

The research on long traveling-wave antennas is aimed at finding their maximum practical directivity. Results to date indicate that this maximum length is set by a combination of several factors: ohmic attenuation in the conductors of the antenna, inability to control the radiation pattern when the antenna is very long, and restricted pattern bandwidth. Determination of the attenuation of waves guided by the antenna has been carried out both experimentally and theoretically, the latter work involving use of the IBM 709 computer. Experimental measurements of models of traveling-wave antennas have been carried out by using the Department's newly acquired antenna-pattern range facilities.

Early work on this project was confined almost entirely to antennas of the Yagi type, involving long arrays of parallel metal rods. Limited success with this structure led to the investigation of more promising types, known as driven end-fire arrays. The photograph of a small-scale experimental model of such a driven array is shown on the next page.

Rapid-Scan Antennas

Most radar systems employ a narrow beam of electromagnetic radiation that is scanned throughout a certain angular range by means of the physical orientation of the antenna. There has been continuous interest, practically since the early days of radar, in the development of means for scanning the beam without the necessity of moving the entire antenna. If the inertia of the antenna could be removed, rapid scan rates would be possible, bringing about a number of desirable improvements in the radar system.

During the past year, a research program has been carried out under Air Force sponsorship to investigate a new type of rapid-scan antenna. The fundamental principle of operation is not new: use is made of a linear array of radiators, driven from a wave-guiding structure that serves to excite the radiators with currents whose relative phase may be controlled, causing the resulting radiation pattern to be scanned. The novel aspect of this research is the nature of the wave guide exciting the array. Use is being made of a class of structures supporting a so-called surface wave, which is caused to propagate at a velocity in the range of 20 to 30% of the speed of light. Methods have been investigated of varying the phase velocity of the guided wave by some simple mechanical motion, such as the rotation of a shaft, which could be accomplished at relatively high speed. Variation of the wave velocity causes the radiators, which are coupled to the wave-guiding structure, to be excited with variable relative phasing. The types of slow-wave structures studied have included arrays of closely spaced metal strips, metal squares and discs, rings, and metal strips printed on dielectric laminate, in the same manner as printed electric circuits.

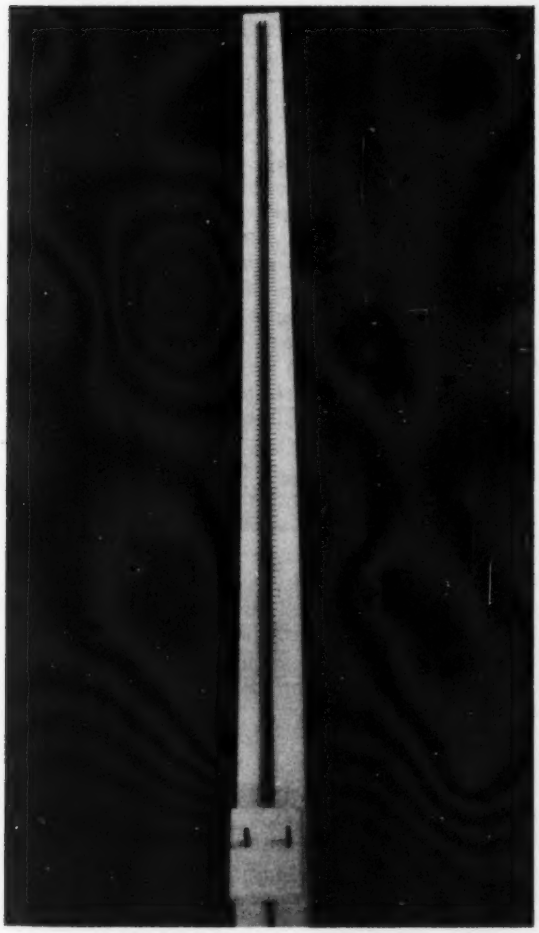
This work has been carried out under sponsorship of the Air Force Cambridge Research Center.

D. K. REYNOLDS,
Professor of Electrical Engineering

* D. K. Reynolds, "Very Long Traveling Wave Antennas," Technical Report 1, Contract Nonr-3091(01) (X), Dept. of Electrical Engg., U. of Wash., June, 1961.

Statistical Theory Applied to Antennas

Since the electrical properties of the ionosphere and of the troposphere vary from point to point, electromagnetic energy transmitted through or reflected from these regions undergoes distortion. This distortion, appearing as random attenuations and delays, is affected by the antenna patterns of the transmitter and of the receiver. For example, often the energy travels along several well-defined paths, resulting in different arrival angles at the receiver for the energies transmitted over the various paths. Since the paths will generally have different (and continually changing) attenuations and lengths, the signal energy at the receiver will consist of a superposition of attenuated and delayed waveforms of the transmitted signal. A narrow antenna pattern may be able to select just the energy from a particular path, and may thus reduce the uncertainty as to the true nature of the transmitted signal. In many systems, the arrival angles continually vary, and an extremely narrow antenna pattern may receive no signal during some periods. Some compromise is therefore indicated in the selection of an antenna pattern.



SMALL-SCALE EXPERIMENTAL MODEL OF DRIVEN END-FIRE ARRAY

The work carried out at the University has enabled the specification of such statistics as the autocorrelation function of the received signal. The form of the specification permits an evaluation of the effects of the path attenuations, arrival-angle variations, transmitted waveforms, and antenna pattern. A comparison of the correlation functions of the received and transmitted ensembles serves as one indication of the signal distortion in the transmission process.

Signal distortion because of transmission anomalies has been much considered in the literature, but most efforts to include the effects of the antenna pattern have been predicted on the scatter-propagation mode, and have assumed particular scattering cross-sections models. The hypotheses required to develop these results are not compatible with conditions in systems relying on reflections from the more well defined tropospheric or ionospheric layers. The present research is aimed at providing an analysis applicable to situations involving reflection phenomena.

In some instances, a particular feature of the received signal—perhaps the phase or the envelope amplitude—may be the only information-bearing quantity. Consequently, methods for computing the statistics of these quantities have been devised.

Useful as these statistics are in evaluating the effect of the antenna pattern on the performance of a communications system, they provide something less than the answer desired for the question, "Exactly how much information can be transmitted over a particular system?"

A portion of the work here at the University provides the answer to this question when the distortion phenomena are of a certain type, and provides an extension to the literature* published on systems undergoing such distortions. Results of the University work have been reported in detail.**

H. M. SWARM,
Professor of Electrical Engineering

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* G. D. Hulst, "Inverse Ionosphere," IRE *Trans.* on Communication Systems, Vol. CS-8, March, 1960, pp. 3-9.

** D. D. McNelis and H. M. Swarm, "Antenna Patterns for Maximum Information Rate under Simple Multi-Bath Conditions," Report No. 49, US Air Force (Cambridge) Contract No. AF19(604)4098; D.D. McNelis, "The Effect of the Antenna Pattern on the Statistics of the Received Signal in Radio-Frequency Propagation Systems," Ph.D. Thesis, U. of Wash., 1961.

RADIO-PROPAGATION RESEARCH

The research of the Radio Propagation Group has expanded during the last few years to include extensive installations at the West Seattle Laboratories field site and at the Kenmore Laboratory field site. The data collected at these sites are usually on magnetic tape, paper chart, and photographic film. The analysis of the experimental data and the theoretical explanations are performed by the graduate students in the Electrical Engineering and Research Computing Laboratories. These research projects include (1) Long-Distance Ionospheric Doppler shift of CW signals, (2) Properties of Ionospheric Layers, some aspects of which are summarized in the following sections, (3) Radio Astronomy research initially to be concerned with the solar phenomena, and (4) a program for studying the properties of Whistlers. The latter projects are currently being instrumented and will be activated during this summer.

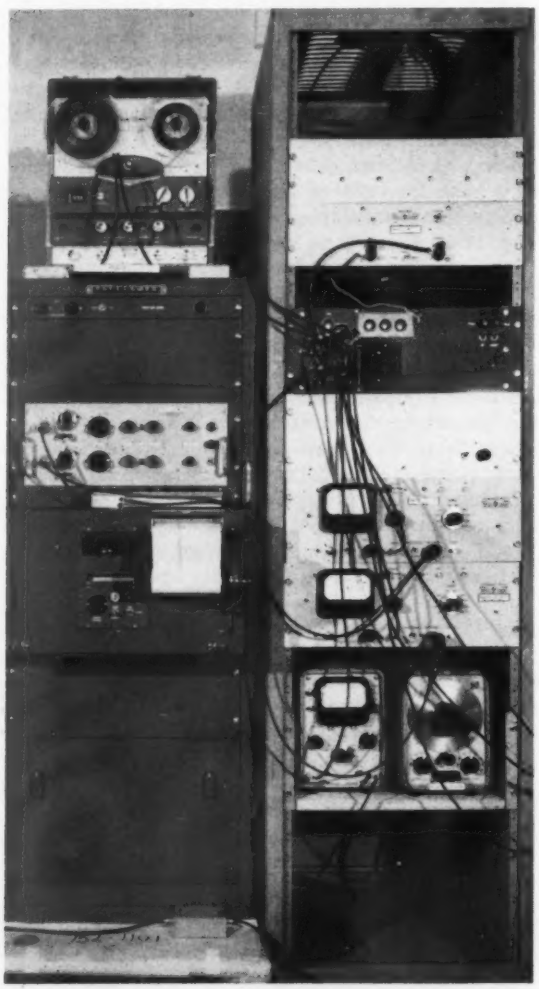


FIG. 1. DOPPLER-SHIFT RECORDING EQUIPMENT

Ionospheric Doppler Shift of CW Signals

The natural diurnal variations of the ionospheric-layer heights cause a substantial change in the path length of long-distance signals propagated by radio waves. The frequency of the received signal is hence shifted by a small amount called the Doppler frequency. If two modes of propagation are present at the same time, the received signal not uncommonly consists of two slightly different frequency components; hence two Doppler frequencies are present simultaneously. Sometimes one of these may be increasing while the other is decreasing.

The behavior of the Doppler frequency components of a received signal is a fascinating study. A part of this fascination is the theoretical considerations of the behavior of the ionosphere necessary to explain the Doppler data. Supplementing this data is the transmission-time delay of pulsed signals and the correlation of delay phenomena with the Doppler effects.

The instrumentation for recording the Doppler frequency and field strength of several signal channels is shown in Fig. 1; the antenna arrays for the various receivers and the building housing the instrumentation equipment are shown in Fig. 2.

This project has obtained a great amount of experimental data during the past year. The detailed analysis and explanations of the phenomena producing the resulting data are far from complete. A part of the completed analysis has resulted in several classified reports in collaboration with the Radioscience Laboratory at Stanford University.

Heights of Electron Density and the Earth's Gyrofrequency

The fact that the ionospheric layers are subject to lunar tidal variations has been very well established for about two decades. The lunar tidal effects may be quantitatively obtained by calculating the amplitudes and phases of the semidiurnal sinusoidal oscillations in the heights and critical frequencies of the ionospheric layers. Several research workers have carried out investigations to this effect, by routine analysis of virtual height vs. frequency records (i.e., ionograms), at different geographic locations for different periods. N. N. Rao and the author compared these experimental results with ones they derived from an extension of the work on ionospheric tidal theory (*Trend*, April, 1960). They found the theoretical results of the semidiurnal lunar variations in the F-layer parameters to be in fair agreement with those derived from the experimental data. However,

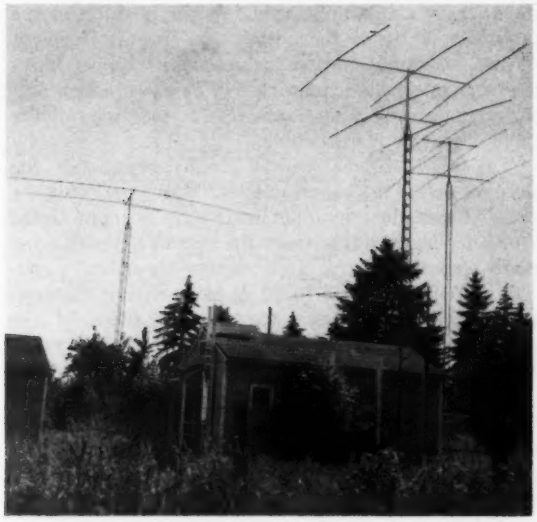


FIG. 2. RECEIVING ANTENNAS AND EQUIPMENT SHED

for the E-region, discrepancy was reported. Two reasons offered to explain the discrepancy are (1) the experimental work at different locations was done at widely separated intervals of time, so that the results lack consistency, and (2) all of the experimental results have come from an analysis of the virtual heights of the ionospheric layers rather than from actual, or true, heights.

The importance of the analysis of the true-height data has then been recognized, and attention has been diverted to a study of the various existing methods of obtaining electron-density vs. true-height data from the raw ionograms. The most widely used method is the Budden* matrix method, which utilizes the information from the ordinary ray virtual-height curve only. This method assumes a monotonically increasing electron density-height profile; it requires that the original virtual-height curve extend down to zero frequency. However, none of these conditions are fulfilled in practice, with the result that the computed electron-density profile is not unique, especially near the low-density ionization. Extensions of the Budden matrix method that utilizes both the ordinary and extraordinary virtual-height curves have been suggested to remove this ambiguity. L. R. O. Storey recently suggested such an extension.**

Storey points out the already anticipated difficulty that might be encountered in the practical use of his method. This difficulty arises from the lateral deviations in the otherwise vertical paths of the ordinary and the extraordinary rays within the ionosphere, whenever latitude gradients of electron density are present. The ordinary ray is deflected towards the poles; the extraordinary one towards the equator. In such a case, neither of the two virtual-height curves corresponds to the vertical distribution of ionization directly above the ionospheric recorder. A correction has to be applied to the computed electron-density profile, depending upon the gradient of ionization. Fortunately, there is a way of obtaining this information from the virtual height-frequency record itself.

Investigators have found that calculations of the gyro-frequency utilizing the critical frequencies read from the ionograms yielded in general a greater value for the magnetic field, compared to that extrapolated from the value at the earth's surface according to the inverse-cube law. This effect has rightly been attributed mainly to the ray-path deflections in the ionosphere, along with other reasons. In all these investigations, true heights of the layer were not considered, and it was thought worth while to determine how the gyrofrequency computed from the ionograms varies with the corresponding true height.

Accordingly, to study this effect, 51 carefully selected ionograms, obtained at Seattle during the nights of five magnetically quiet days in October, 1958, were analyzed. The true-height profile for each ionograms was computed by using the Budden matrix method, and the gyrofrequency calculated from the critical frequencies. A plot of the gyrofrequency vs. true height is made (as shown in Fig. 3), and the equation for the best-fit straight line is determined.

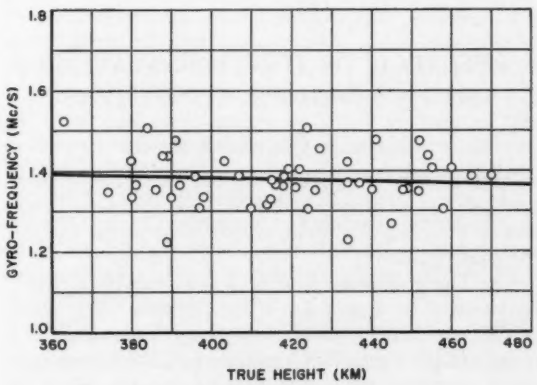


FIG. 3. GYROFREQUENCY VS TRUE HEIGHT OF THE IONOSPHERIC LAYER OVER SEATTLE

* K. G. Budden, "A method for determining the variation of electron density with height [N(z) curves] from curves of equivalent height against frequency [(h', f) curves]," *Report of Cambridge Conf. Ionospheric Physics,* Phys. Soc., London, 1955, pp. 332-339.

** L. R. O. Storey, "The Joint Use of the Ordinary and Extraordinary Virtual Curves in determining Ionospheric Layer Profiles," *J. Research NBS,* Vol. 64D (Radio Prop.), No. 2, March-April, 1960, pp. 111-124.

Extrapolation of each computed value of the gyrofrequency to the earth's surface according to the inverse-cube law resulted in an average of 1.716 Mc, whereas the actual value is 1.594 Mc. If this discrepancy between theory and practice can be utilized to deduce the magnitude of the horizontal gradient of electron density in the ionosphere, then a correction can be applied in the computation of the electron-density profiles.

Further work has been initiated to correlate the horizontal gradient and the gyrofrequency. Data from the NBS vertical-incidence ionspheric sounding stations in Puerto Rico, Grand Bahama Island, White Sands, Mt. Monmouth, and St. Johns (situated approximately along the 75° W meridian) can be utilized for this purpose with great advantage. From the computed electron-density true-height data for these stations, vertical cross sections of the ionosphere along the 75° W meridian are being drawn and the approximate horizontal gradient of electron density determined for each station. From a theoretical analysis of the direction of energy flow in the ionosphere, the lateral deviation of the ordinary and extraordinary modes of propagation, and hence the expected value of the gyrofrequency, will be determined. This can then be compared with the value computed from the critical frequencies read from the ionograms, to achieve the desired goal. With this purpose, the present work may be able to achieve significant results in true-height research.

These research projects have been supported by the Air Force Cambridge Research Center; the Office of Naval Research; the National Defense Graduate Fellowship Program of the Dept. of Health, Education and Welfare; and the National Bureau of Standards.

H. M. Swarm,
Professor of Electrical Engineering

RESEARCH IN CONTROL SYSTEMS AND IN DIGITAL COMPUTERS

Adaptive Control Systems

The research approach to the adaptive control problem, as distinguished from the ordinary problem of the control system, is described in the following paragraphs.

The block diagram in Fig. 1 is a simplified representation of an automatic control system. The plant is the mechanism or process being controlled, the output is the controlled variable, and the plant-actuating signal is the agent that causes the plant to change its state. If, for example, the plant is the table of an automatic milling machine, driven along its ways by a hydraulic actuator, the position of the table can be called the output and the displacement of the hydraulic control valve (which ports high-pressure oil to the actuator) will be the plant-actuating signal. Any unexpected forces existing on the table would be disturbances.

The input signal, which usually represents the desired state of the output, is often corrupted by noise; hence the controller with a noisy input signal and a feedback signal from the output generates the plant-actuating signal. In designing an ordinary control system, the basic problem is to design the controller with given dynamic characteristics of the plant, disturbances, and noise, which are assumed to be constant during the operation.

In recent years a new type of design problem has arisen, called the adaptive control problem, that occurs where the characteristics of the plant, the disturbances, the signal, or the noise do not remain constant but vary during operation. A controller designed according to ordinary servomechanism principles can accommodate small variations in these characteristics: only when the variations become gross is the problem one in adaptive control. An adaptive controller might appear as shown in Fig. 2. Here a third component, called an adaptive computer, must sense the changes taking place in the system and generate the required adjustments to be made in the controller.

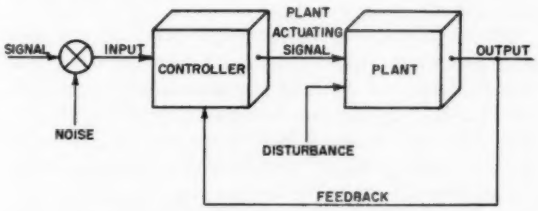


FIG. 1. AUTOMATIC CONTROL SYSTEM

Analysis of an adaptive control system is more complex than that of a conventional system since the differential equations describing the system are not time invariant as are those in conventional systems. At best, the equations are ordinary linear equations having time-variable coefficients; at worst, they are nonlinear, having time-variable coefficients and being subjected to nonstationary random-forcing functions (input and disturbance).*

The work in adaptive systems here has been limited to a "plant adaptive" problem, where we assume that changes occur only in the plant; changes in the signal, noise, and disturbances are not considered.

* Bellman, *Adaptive Control Processes*, Princeton U. Press, 1961; Mishkin and Braun, *Adaptive Control Systems*, McGraw-Hill, 1961.

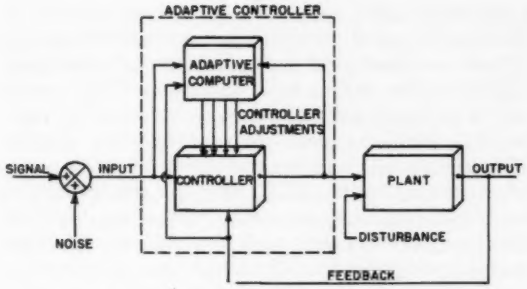


FIG. 2. ADAPTIVE CONTROL SYSTEM

Two possible approaches to the plant-adaptive problem are: (a) a "plant-measuring" scheme in which dynamic measurements are made on the plant by the adaptive computer to determine directly the changes in the plant parameters, and (b) a "performance-measuring" approach in which the performance of the system is monitored and compensatory adjustments are made in the controller to improve the performance. Attention has been limited here to the performance-measuring approach.

A specific plant described by four parameters, M, a, K, and l, was selected for this study. Sixty different numerical combinations of these parameters (plant conditions) were defined. Variations in parameter magnitudes were as high as 600 to 1, and the static sensitivity of the plant, a function of all four parameters, varied over a range of 50,000 to 1. In one-third of the plant conditions the plant is dynamically unstable. The variations in the plant parameters were assumed to occur in finite steps, the plant remaining fixed for a period of time in one condition and then changing in step-like fashion to the next condition.

The major objective of the research is to find a design for the adaptive computer that will keep the performance of the system within acceptable bounds and at the same time minimize the period of time during which the plant parameters must remain fixed. The particular performance measure used is I, the integral of error squared:

$$I = \int_0^\infty \epsilon^2(t)dt, \qquad (1)$$

where $\epsilon(t)$ is the system error occuring in response to a unit-step input. It was determined that a linear controller having four parameters, K_3, K, P, and Z, could accommodate all sixty plant conditions with extremely small error if the parameters were variable over wide ranges. Because both plant and controller are assumed to be linear, I can be expressed as an algebraic function of the eight parameters, M, a, k, l, K_3, K, P, and Z. This lengthy expression cannot be handled practically except with the aid of a digital computer.

The adaptive control system was simulated on the digital computer, the flow diagram for which is shown in Fig. 3. Here the performance index, I, is computed as a function of the plant and the controller parameters. If I is less than the acceptable value, the plant is advanced to the next condition by the adaptive computer; but if I is greater than the acceptable

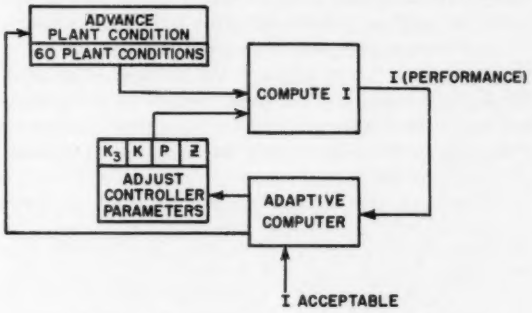


FIG. 3. DIGITAL-COMPUTER SIMULATION

value the adaptive computer must adjust the controller parameters in order to reduce I below the acceptable limit. The problem of designing the adaptive computer is simply one of finding an efficient minimization scheme, one that finds the optimum settings for the controller parameters with as few iterations of the "Compute I" operation as possible. At the University a modified form of the Hestenes-Stiefel method of steep descent was found to work satisfactorily when only two of the plant parameters were variable; however, with four plant parameters variable a new scheme of minimization became necessary.

The simple logical scheme devised, a "relaxation" method, worked quite well in all 60 plant conditions. In this scheme the controller parameters are changed by fixed percentages of their present values; no gradient information need be generated by the adaptive computer. The percentages are different for each controller parameter; they were determined from studies of the I function. Digital-computer runs showed that this "relaxation" scheme adjusted the controller parameters with an average of 19 iterations of the I computation per plant condition. Work is continuing on the relaxation method to reduce this number of iterations.

Equation (1) shows the performance measure, I, to be an infinite integral and therefore unsuited for use in a real system. In practice a truncated form of this integral would be used,

$$I_T = \int_0^T \epsilon^2(t)dt. \qquad (2)$$

It is desirable, of course, to have the truncation time, T, as short as possible, as this minimizes the time required for adaptation. However, if T is too short the logical design of the adaptive computer, which is

based on the response of I to changes in K, K_3, P, and Z, would fail. To determine the best value for T and also the effects of instrumentation errors the system was simulated on the analog computers, since I_T cannot be conveniently evaluated with the digital computer. These tests showed that T must be at least as long as the response time of the system in its optimum state, and that the squaring and integrating operations could be carried out with sufficient accuracy.

Performance measure, I_T, is based upon the error in response to a step input to the system. This artificial input could not be employed in a real system having a random input: there an approximation to the mean-square error would be used as the performance measure,

$$I_M = \frac{1}{T} \int_0^T \epsilon^2(t)dt. \qquad (3)$$

where ϵ (t) is a random function. If the input is a stationary random function, I_M is a function of K, K_3, P, and Z, which is very similar to I (as $T \to \infty$). We can therefore reasonably expect a logical scheme based upon I to work with I_M as the input to the adaptive computer. No artificial input is required with I_M as the performance measure. Work directed toward evaluating this hypothesis is currently in progress.

R. N. CLARK,
Associate Professor of Electrical Engineering

Digital Computers

Research in the application and design of digital computers has been extremely active during the past year in this Department. The areas of research fall into several different categories, as follows: (1) logical analysis; (2) logical design; (3) machine evaluation of mechanical translations; (4) pattern recognition analysis; (5) man-computer interface studies; and (6) analysis and solution of the multiple-reservoir hydro-usage problem.

Recent research in logical analysis has included projects developing analytical methods for solution of trinary systems; analysis and solution of means for extension of logical reliability through Boolean matrix and probabilistic methods; and an analysis and conceptual solution of logical propositions with the digital computer. The latter study has very real implications for machine "intelligence."

The bulk of research in logical design has concerned design of unique special-purpose digital-control elements. Analysis and synthesis have been used to define optimal logical design of the devices.

The project related to evaluation of mechanical translations of natural languages evolved from research into the theory and techniques of mechanical translation, which has been a joint effort of the Far Eastern Department and Electrical Engineering. An objective evaluation of the product of the mechanical translation has so far been impossible. To provide such a measure, research has been aimed at developing a probabilistic measure of translation quality. The original text and the translation undergo parallel processing by the IBM 709; the result includes evaluation of translation word order, word insertion, validity of equivalents, and the sufficiency of the translation dictionary. All evaluations made by probabilistic means are valid only for relatively large translation samples.

Pattern recognition is essential for the input of mechanical translation devices. Automatic readers allowing direct and high-speed coding of written text are required before mechanical translation can be economically competitive with human translation. Various means of pattern recognition involving parallel scan of printed materials have been developed recently, one of which allows considerable deformation of characters. Analysis of identification of severely deformed characters by contextual and probabilistic means is one area of current investigation.

A current research project investigates the existence and placement of the "man-computer interface," i.e., the optimal boundary dividing responsibility of humans and computers in solutions of system problems. In the past, a requirement was that computer function be maximized to the greatest possible extent. Recent computer developments, as well as great strides in levels of computer applications, have caused serious questions as to the degree of human participation that is desirable and necessary. Since it seems certain that human participation will rarely become necessary in a vast spectrum of scientific and social problems, the actual question of "Where?" relates primarily to the boundary required by efficiency and human standards of judgment or perception.

Research in Hydro Usage

Two research projects being carried out in the Department relate to analysis and solution of multiple-reservoir hydro-usage problems. The problem structures and solution approaches are considerably different. In the Pacific Northwest, as in numerous places where hydroelectric power resources are significant, obtaining optimal use of actual or anticipated resources is very important economically. As local power usage becomes more intimately related to that of California and Canada, a practical analysis of resource usage in hydroelectric facilities must be increasingly general in application. One approach to this problem will be summarized as a sample of this kind of departmental effort.

Hydro usage for generation of power has been a critical problem to hydroelectric power systems as long as reservoirs have been considered in the capacity of energy-storage units. The basic relationships have been frequently discussed, but in hydroelectric systems the complex relationship between storage usage of river-connected reservoirs is difficult to express. The determination of storage withdrawal sequencing and proportionment to meet demands over a given annual time period has in the past been accomplished by engineering experience and logic related to past performance and to characteristics of the specific system being observed.

The quantity of power derivable from a given hydroelectric installation at a given time is a function of turbine flow, effective head, and turbine efficiency. Unit efficiency is usually assumed to be either constant over normal operating ranges or a function of turbine flow. With spillage neglected, turbine flow is equal to the sum of the storage discharge and the reservoir inflow; i.e., the time derivative of reservoir storage plus inflows. Effective head is calculated as the difference between forebay elevation and tailwater elevation. Forebay elevation can be expressed as a function of reservoir storage; tailwater elevation can be determined as a function of total discharge. Ultimately the power developed by a given hydroelectric installation can be described for any given time with reservoir storage as a function of time and the storage-time derivative as the only variables:

$$P=f(Q, \dot{Q}). \tag{1}$$

Parameters of the functional description will be fixed by the physical and electrical characteristics of the specific installation but will be of a common form.

Restrictions in the form of maxima and minima in forebay elevations, total discharge, and plant discharge multiply the complexity of the hydro-usage problem.

One method of calculation currently being studied in this research is based upon the Calculus of Variations.* It endeavors to minimize a hypothetically constructed cost function over the entire period under consideration. Since different operating restrictions enter into the solution only indirectly as modifications of the cost function, this method can be easily modified to suit the different systems and criteria of optimization. The method of solution is discussed in terms of a system of two reservoirs and one thermal plant, the latter being assumed to have sufficient capacity to meet any power deficit. The inflow curves to the two reservoirs and the load curve are assumed to be known.

Since the power generated at a plant is a function of the storage and its rate of change, the total hourly cost of deficit power to be supplied by the thermal plant will also be a function of the storages in the two reservoirs and their rates of change. The method for restricting the operation within prescribed limits, to make any violation of restrictions extremely expensive, is applied by "penalty costs" ranging from zero when no restriction is violated to a large cost for violation. The total cost of operation, defined as the sum of the deficit cost and the penalty costs at any interval of time, is represented by \$/hr.

Since the total cost per hour is a function of time, storages, and their time derivatives, the problem is reduced to one within the Calculus of Variations, with fixed end points. It can be stated as follows:

$$\int_0^T \$/\text{hr}(Q_1, Q_2, \dot{Q}_1, \dot{Q}_2, t)dt = \text{minimum} \tag{2}$$

and

$$Q_1(0)=K_1;\ Q_2(0)=K_2;\ Q_1(T)=K_3;\ Q_2(T)=K_4,$$

where the K's are constants.

Using standard techniques of the Calculus of Variations, we show that the necessary conditions to be satisfied by a solution are the Euler-Lagrange equations

$$\frac{\partial \$/\text{hr}}{\partial Q_1} - \frac{d}{dt}\frac{\partial \$/\text{hr}}{\partial \dot{Q}_1} = 0 \tag{3}$$

and

$$\frac{\partial \$/\text{hr}}{\partial Q_2} - \frac{d}{dt}\frac{\partial \$/\text{hr}}{\partial \dot{Q}_2} = 0. \tag{4}$$

In a solution attempted on the IBM 650 by using the method of steepest descent suggested by Cypser, beginning with assumed storage curves, the total cost decreased steadily after each iteration, oscillations of the storage curves began, and the solution did not converge. Other methods of solution of the Euler-Lagrange equation are currently being investigated.

Although the research is not yet complete, sufficient data have been obtained to indicate that an optimal solution to the hydro-storage problem can be obtained in a generalized form through the Calculus of Variations. Analytic methods have been developed to consider the system restrictions in the problem solution, but further investigation must be carried out to prove the efficiency and generality of these methods. Additional research is aimed at determining various criteria of optimization that can be obtained by such solutions of the hydro-usage problem.

D. L. Johnson,
Professor of Electrical Engineering

* R. J. Cypser, "The Optimum Use of Water Storage in Hydro-Thermal Electrical Systems," Sc. D. Thesis, M. I. T., Jan., 1953; "Computer Search for Economical Operation of a Hydrothermal Electric System," AIEE *Trans.*, Vol. 73, Pt. III-B, Oct., 1954.

Civil Engineering

R. B. VAN HORN, *Executive Officer*

Through the years the volume of work in Civil Engineering supplementary to teaching continues to grow. The biggest increase has been in sponsored research. Although the direction of the research has not shifted, the emphasis has changed. Especially notable in recent years have been the large-scale studies undertaken for branches of the State and Federal governments.

To keep the examples offered here of work done in the Department detailed enough to be meaningful, they had to be strictly limited in number. No attempt was made to represent adequately the five divisions—transportation, hydraulics, sanitary, structures, and materials—that make up the Department. Rather, the summaries that follow are characteristic of work being done in these divisions, and they do represent some of the current emphasis.

Research within the Transportation and Materials Council

In recent years, the Civil Engineering Department has undertaken several important research projects in transportation engineering. Most of these have been studies made at the request of and with the financial support of the Joint Fact-Finding Committee on Highways, Streets and Bridges of the Washington State Legislature. They have been made under the general supervision of Professor Robert G. Hennes, who has kept close liaison with members of this Interim Committee and all interested agencies and organizations. As a consequence, the resulting reports have merited the approval of the Interim Committee and have benefited the people of the State.

One of the first of these research programs, a study made jointly with Washington State University in 1952, was entitled "State Interest in Highways." This basic highway classification study established a means of determining State interest in the various sections of highway for providing service to population centers, to the various industries of the state, and to recreation. The study has provided the Legislature and the Highway Department a yardstick to use in deciding which roads and streets should remain or become a part of the State primary and secondary systems, and which should be under a county or city jurisdiction.

The second major study undertaken for the Interim Committee, an "Allocation of Road and Street Costs" also made jointly with Washington State University, was completed in 1956. It has been a guide to equitable division of road-cost responsibility among the three principal direct beneficiaries, the highway user, the owners of affected property, and the general public; and it has helped provide an equitable division of the users' share of these costs among the various types of automobiles, trucks, and busses that operate on Washington's roads and streets. The report, published in ten volumes, presents a comprehensive analysis of highway cost allocation. In addition to providing a guide for the Legislature, this publication has been mailed on request to many other states and to individuals and agencies.

These titles are a partial listing of more recent research in transportation engineering: *Equitable Alternatives in Highway User Taxation, Motor Vehicle Administration in Washington, Geographic Impact of Highway Improvement, Federal Interest in Forest Highways, Influence of Highway Improvements on Urban Land, Studies of the Central Business District and Urban Freeway Development, Motor Benefits Study,* and *Washington Street and Highway Need Study.* Most of these research projects have involved many disciplines of the University. The College of Business Administration; the College of Architecture and Urban Planning; and the Departments of Economics, Geography, and Mechanical Engineering have worked closely with Civil Engineering in these research efforts. Many graduate students in the several disciplines have participated as research assistants and have applied their contributions toward requirements for advanced degrees.

To cope more effectively with problems of transportation, a Transportation Research Group was established at the University during the Spring Quarter of 1960. It is composed of members of the graduate faculty from four colleges of the University who have a common interest in transportation, or in the social, political, and economic consequences of improvements in transportation. The aims of this Transportation Research Group are as follows:

1. To explore and encourage research on transportation problems of national or regional concern;
2. To provide a means for effective application of the University's resources for inter-disciplinary transportation research;
3. To provide a focus for faculty interest in originating, seeking and conducting transportation research;
4. To provide a means of giving continuity to highway-research projects currently under way;

5. To provide a means of channeling transportation-research studies to the most appropriate members of the University faculty; and

6. To help attract able graduate students to the University and to assist in the effective use of University resources for their training.

A continuous research program has been maintained in the fields of soil mechanics and paving materials. This program has been geared to the demands of the civil engineering profession, and has met the research needs of graduate students seeking both master's and doctor's degrees.

In recent years, there has been an increasing demand for graduate work in urban planning and traffic engineering. This has been met by increasing the number of course offerings in these fields and by providing facilities and opportunities for research.

M. I. Ekse,
Professor of Civil Engineering

Federally Sponsored Research in Highway Economics

Spurred by the growing demand for highway investment in the mid-fifties, the Federal government has become active in sponsoring research that will aid in the knowledge of how different segments of society benefit from highway improvement and how they shall be taxed accordingly. This is generally known as highway economic-impact research and highway cost-allocation study. The State of Washington, mainly under the impetus of the transportation personnel in the Civil Engineering Department, had done leading analysis in this field for almost a decade before Federal interest burgeoned forth. It was opportune therefore for the University to enter into research contracts with the Bureau of Public Roads in these areas.

The first highway economic-impact research done by the University for the Federal government was in the 1957-59 biennium. The author directed this research; Professor William L. Garrison of the Geography Department shared responsibility for the study, and phases of the work were done by Professor Leonard L. Goldberg of the College of Business Administration.

This study led to two volumes produced by the University of Washington Press in 1959 entitled *Studies of Highway Development and Geographic Change,* by William L. Garrison, *et al.,* and *Studies of the Central Business District and Urban Freeway Development,* by Edgar M. Horwood and Ronald R. Boyce. The first of these volumes involved significant field-research work in different parts of the State and gave new insight into the changing use of highway facilities as well as the effect of transportation improvement on the location and organization of retail activities. This was deemed to be a leading work of its type, and Professor Garrison was commissioned by the Bureau of Public Roads to prepare a followup manual to aid the separate states in conducting similar studies.

The second volume in this series deals with the impact of urban freeways usage on the city center itself, develops theories of the structural organization of land use in the city center, and presents an analytical basis for predicting changes in the main categories of central land use with time and with city growth. The latter changes can be readily equated to changes in the demand for urban transportation during the peak hours. Both of these volumes have recently been reprinted. Results of this first series of studies were incorporated in the national cost-allocation study authorized by the Federal Highway Act of 1956 and reported to Congress in 1959.

Highway economic research sponsored by the Federal government during the current biennium mainly concerns policy and investment decisions that will have to be made as the new highway system is developed and comes into operation in urban areas. This research primarily addresses itself to the problems of relating land development to highway development, of the advisability of regulating land development in freeway approach zones, of the status of local planning policy in respect to highway problems, and of the demand for industrial and commercial sites in urban areas proximate to freeway locations. Professor Garrison and the author again collaborated in the work; and Dr. Duane F. Marble of the University of Pennsylvania did a supplementary part of the study dealing with the needs of through travelers.

Altogether, close to $100,000 have been allocated to these federally sponsored projects in highway economics. This type of research has involved a broad interdisciplinary team of personnel from within the College of Engineering and from other areas of the campus. New research proposals are currently being submitted for continued studies in these fields as well as methodological and quantitative studies in certain aspects of regional analysis. Federal interest in this type of research stems from the complexity of planning public facilities in our contemporary society, and reflects new demands on engineering education, particularly at the graduate level and in terms of these broad environmental fields of analysis and research.

E. M. Horwood,
Associate Professor of Civil Engineering

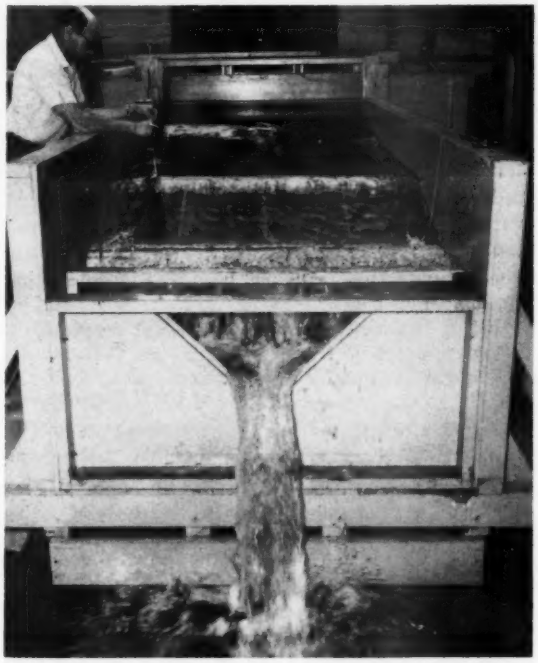
Recent Hydraulic Research

A summary of the research undertaken at the Charles W. Harris Hydraulic Laboratory during the past five years demonstrates its accomplishments and potentialities, though space limitations mean that only projects of major scope can be included. Most of the research has been of an applied nature, serving the purpose of determining the hydraulic behavior of one or more basic components in various combinations, and it has largely been sponsored by the Federal or local government agencies. The laboratory plant has recently been enlarged so that facilities are now available for investigations of all but the very largest hydraulic problems. The following description outlines the nature of the principal investigations undertaken.

Mayfield Dam: Downstream Migrant-Fish Skimmer. A 1:3 scale model was used to determine whether the hydraulic performance of the downstream skimmer in the facilities at this dam would provide for the safe passage of fish, remove excess water with the least possible head loss, and minimize the need for manual control or maintenance. The final design consisted of a screen inclined slightly upward in the direction of flow with slatted orifices beneath the screen to assure proper velocities along the skimmer for the bypass water containing the fish. Professor E. P. Richey supervised this study, which, like the next one described, was sponsored by the Major Projects Division, Tacoma Department of Public Utilities.

Mayfield Dam: Upstream Migrant-Fish Ladder. The 1:10 scale model was a complicated open channel required to maintain certain standards of flow throughout the operating range of tailwater conditions. Its purpose was to check the initial design and to permit observation of flow conditions for different arrangements of the basic components of the system. No new hydraulic concepts were disclosed; however, it provided a rapid way of showing how a wide variety of different control features could be brought together that would have been impractical to attempt by theory alone. Professor H. H. Chenoweth assisted Professor Richey in this work.

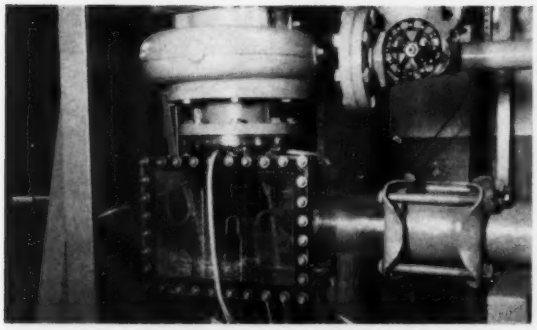
ARD-37 Auxiliary Floating Drydock, Sump-Suction Chest. A model was designed to determine flow conditions in the pump-suction box of the ARD-37 drydock and to ascertain the velocity distribution at the pump-suction connection. Pressure measurements were made to determine points of incipient cavitation. The flow pattern was observed visually and photographically recorded. Velocity traverses by pitot tube and pressure measurements by piezometers were made throughout the chest without encountering any serious defects in the design. Sponsor, W. C. Nickum and Sons; investigators, Professors H. K. Moritz and W. M. Miller.



MODEL OF DOWNSTREAM MIGRANT-FISH SKIMMER AT MAYFIELD DAM

South Fork of Tolt River Spillway. An investigation of spillway entrance design, determination of a spillway rating curve, and a study of the means for diverting the flow at the foot of the spillway chute were undertaken by use of a model. Improvements were made to the spillway entrance geometry and a satisfactory scheme for harmlessly deflecting the flow by the use of diverter blocks was effected. Sponsor, the Board of Public Works, City of Seattle; investigators, Professor Richey and the author.

Tolt River Water-Supply System: Energy Dissipator. A 1:8 model was used to study a design for dissipating excess energy in a segment of the Tolt River pipeline. A duplication of the manifold system at the lower end of the h-p line leading from the reservoir to the junction with the l-p line was simulated. The design was verified, and the necessary modifications to permit shortening of the discharge pipe and to eliminate sources of dangerous low pressures were made. Sponsor, the Board of Public Works, City of Seattle; investigators, Professor Richey and the author.



SETUP FOR STUDY OF PUMP-SUCTION CHEST

FIRST-DESIGN MODEL OF SPILLWAY, SOUTH FORK OF TOLT RIVER

South Fork Tolt River Spillway, Second Design. A 1:48 scale-model test was made to verify the original design and to determine modifications necessary. The system consisted of a "Morning Glory" spillway, vertical shaft, horseshoe conduit, rectangular channel, steep chute, and stilling basin. Design features such as the arrangement of piers on the spillway crest, discharge characteristics of the weir and conduit, velocity and water-surface profiles in the conduit section, and the behavior of the stilling basin were checked. Several improvements were made in the design. Sponsor, the Board of Public Works, City of Seattle; investigators, Professor Richey and the author.

MODEL OF DOWNSTREAM MIGRANT-FISH BYPASS AT MAYFIELD DAM

High Gorge Dam, Second-Stage River Diversion. A 1:50 scale model was constructed to check the initial plan and make any alterations necessary to pass flood flows on the Skagit River during the second stage of construction. Among the features studied were the operation of the flashboards and sluiceways in the Low Dam, water-surface elevations at the cofferdams, the occurrence of high velocities, and the development of economical corrective measures for unfavorable flow conditions. Undesirable factors such as high elevation of water surface at cofferdam, high velocities, and large standing waves were eliminated or relieved, and a schedule for operation of the flashboards was determined. Sponsor, the Department of Lighting, City of Seattle; investigators, Professors Richey, Chenoweth, and Miller.

Mayfield Dam Downstream Migrant-Fish Bypass. A 1:12 scale model was used to determine the hydraulic characteristics of a primary fish separator consisting of a series of louvered screens and a mitered bend containing guide vanes for directing the flow. Appropriate alterations to the secondary bypass were made; these sent the bypassed flow containing the migrants over an adjustable weir with screening facilities to prevent fish from going through the turbines. Further studies may be desirable to improve the performance of the flow approaching the mitered bend in the primary separator. The louver performance was satisfactory. Sponsor, the Major

Projects Division, Tacoma Department of Public Utilities; investigators, Professor Richey and the author.

H. S. STRAUSSER,
Associate Professor of Civil Engineering

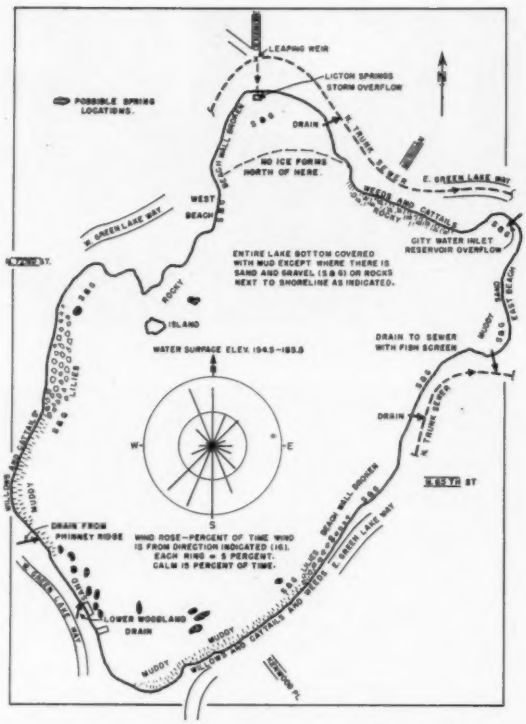
The Green Lake Study

The following paragraphs are a synopsis of a report, *An Engineering and Ecological Study for the Rehabilitation of Green Lake,* which describes an extensive study made at the University for the City of Seattle.

Green Lake, located in the populous northern section of Seattle, has been a subject of repeated controversy concerning its water quality since purchase of the Lake by the Seattle Park Department in 1907. The Lake and its shoreline park area nevertheless have enjoyed an uncommonly high and diversified recreational usage. The full recreational potential has been lessened, however, by nutrient enrichment of the water that causes heavy algae blooms in the summers and by sewage pollution at different times in the Lake's history. Green Lake has a water surface area of 256 acres, a mean water depth of 12.5 ft, mud or sediment depths that in portions of the Lake exceed 30 ft, and a water volume of approximately 1,088 million gal. Physical features are indicated in the accompanying figure.

In the autumn of 1957, the North Trunk Sewer (it serves as a drain for the Lake) collapsed and sewage was backed repeatedly into the Lake during the rainy periods for the next two years. Swimming beaches were closed in the summer of 1958, and the actual condition of the Lake was once more a subject of controversy. In early 1959, the Seattle Park Board asked the University to assist by devising a scheme to permit use of the bathing beaches in the summer of 1959 and by making a detailed study of the actual condition of the Lake, so as to assess the reasons for its condition. The University was to make recommendations for improvement on a long-range basis. A University group made the study and submitted the report prior to the bond-issue election in March, 1959. The author directed this work; he was assisted by Research Assistant Professor George C. Anderson, Oceanography; James A. Servizi, Instructor of Civil Engineering, together with graduate and undergraduate students in civil engineering, oceanography, and zoology, also participated.

The initial phase of the study included field and laboratory work to develop a plan for some type of water purification that would permit opening at least one bathing beach for the coming season. The only


LEAPING WEIR
LICTON SPRINGS STORM OVERFLOW
POSSIBLE SPRING LOCATIONS.
DRAIN
NO ICE FORMS NORTH OF HERE.
E. GREEN LAKE WAY
WEEDS AND CATTAILS
WEST BEACH
N. GREEN LAKE WAY
CITY WATER INLET RESERVOIR OVERFLOW
ENTIRE LAKE BOTTOM COVERED WITH MUD EXCEPT WHERE THERE IS SAND AND GRAVEL (S & G) OR ROCKS NEXT TO SHORELINE AS INDICATED.
ROCKY
ISLAND
WATER SURFACE ELEV. 194.5–195.5
DRAIN TO SEWER WITH FISH SCREEN
MUDDY
EAST BEACH
DRAIN
N. TRUNK SEWER
W
E
S
DRAIN FROM PHINNEY RIDGE
WIND ROSE—PERCENT OF TIME WIND IS FROM DIRECTION INDICATED (16). EACH RING = 5 PERCENT. CALM IS PERCENT OF TIME.
LOWER WOODLAND DRAIN
MUDDY
WEEDS AND CATTAILS
E. GREEN LAKE WAY

MAP SHOWING FEATURES OF GREEN LAKE

scheme that appeared practicable was chosen: lake water was to be pumped out, chlorinated, and then diffused back into the bathing area at the West Beach through the orifices of three plastic pipes 300 ft long. Circulation was to be achieved through flow regulation and utilization of the natural wind-induced currents. Construction of this system was completed in time for use during the 1959 bathing season.

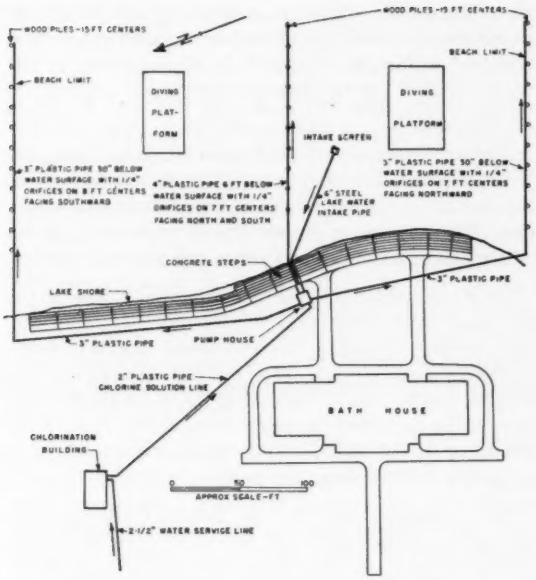
The most significant and important portion of the investigation was the study of the Lake's physical environment, its physical and chemical characteristics, and its ecology. These data were to be used in formulating a permanent plan for lake rehabilitation. Principal study items included the following:

1. Establishment of 17 sampling stations for monitoring at periodic intervals the quality and quantity of lake inflow water; water quality with depth; quality and quantity of lake outflow; and abundance, species, and activity of the biota.

2. Soundings to check water and sediment depths.

3. Collection of bottom-sediment cores for chemical and physical analysis and for a study of the relationship of nutrient exchange at the mud-water interface.

4. Analysis of storm runoff water from nearby arterial and residential streets to ascertain its relationship with the desired quality of lake water.


WOOD PILES-15 FT CENTERS
BEACH LIMIT
DIVING PLAT-FORM
3" PLASTIC PIPE 30" BELOW WATER SURFACE WITH 1/4" ORIFICES ON 8 FT CENTERS FACING SOUTHWARD
4" PLASTIC PIPE 6 FT BELOW WATER SURFACE WITH 1/4" ORIFICES ON 7 FT CENTERS FACING NORTH AND SOUTH
WOOD PILES-15 FT CENTERS
BEACH LIMIT
DIVING PLATFORM
INTAKE SCREEN
6" STEEL LAKE WATER INTAKE PIPE
3" PLASTIC PIPE 30" BELOW WATER SURFACE WITH 1/4" ORIFICES ON 7 FT CENTERS FACING NORTHWARD
CONCRETE STEPS
LAKE SHORE
3" PLASTIC PIPE
3" PLASTIC PIPE
PUMP HOUSE
2" PLASTIC PIPE CHLORINE SOLUTION LINE
BATH HOUSE
CHLORINATION BUILDING
0 50 100
APPROX SCALE-FT
2-1/2" WATER SERVICE LINE

DISINFECTION LAYOUT USED AT WEST BEACH

5. Collections of waterfowl excrement and its analysis for effects on water quality.

6. A general study of water circulation and the most desirable location for inlets and outlets.

7. Ascertaining the actual detrimental qualities of the Lake for recreational purposes and the cause of or source of these undesirable qualities. This included possible sources of sewage pollution, source of nutrients for prolific algae growths, and the seriousness of water shoaling.

8. Relationship of the biota to the environment (chiefly the fish and the plankton) and steps that might be taken to reduce the algal population without seriously harming the fish production.

9. Assembly of a lake history together with past data collected on the water environment.

10. Extent of recreational uses of the Lake and their interrelationship as concerns water quality.

Twenty-three recommendations were made to the City on Lake rehabilitation, the most important being the addition of up to 10 million gal daily of city water, dredging of the shoreline, addition of a new outlet, instigation of a water-quality surveillance program, and the recommendation that storm water not be admitted to the Lake. The Seattle Park Board is now proceeding to implement these recommendations as permitted by available funds.

R. O. SYLVESTER,
Professor of Sanitary Engineering

Motor-Transport Operating Characteristics

The Federal Highway Bill of 1956, which authorized the construction of 41,000 miles of national, interstate, and defense highways, also provided as follows for an investigation into the benefits to be derived from such a high type of highway design: "The allocation of proportionate shares of cost responsibilities among vehicles of different types and sizes is to be used in part on their respective effects

ONE OF THE VEHICLES USED IN THE 1959 STUDY: DIESEL TRUCK WITH SEMITRAILER

on highway costs and in part on the relative benefits derived from the use of the highways." Pursuant to this section of the Bill, the Bureau of Public Roads contracted with four agencies throughout the country to collect data on fuel consumption and travel time of commercial vehicles for variable roadway type and traffic conditions. Through the efforts of Professor R. G. Hennes, who has been active in many research projects for the State Highway Department and the Bureau, the University was chosen as the West Coast data-collection agency.

In the summer of 1958 this study was under the author's direction; he was assisted by Professors J. C. Firey and H. T. Meador of the Mechanical Engineering Department for the primary purpose of instrumentation for collecting data on fuel consumption and travel time. The greatest contribution the University made to this study was that it was the only group to develop a meter for measuring diesel-fuel consumption on the recirculating type of diesel engines. A more detailed description of this metering device was given in the January, 1959, issue of *Trend*. This first study led to an additional one for the State Highway Commission to investigate the variation in fuel consumption in the winter months vs the summer months (when the first study was conducted).

The study is described in a graduate thesis by D. L. Crumbley available at the University, in a report section entitled "Seasonal Variation of Motor Transport Fuel Consumption Rates." This report evaluates the fuel consumption and travel time of diesel-powered vehicles operating over various conditions of rise and fall grades. It utilizes data collected during the summer of 1958 and the subsequent study on seasonal variation, when additional control tests were run and data collected. These data have been instrumental in stimulating additional interest by the Bureau of Public Roads in subsequent research projects.

In the summer of 1959, under a contract with the Bureau of Public Roads and the Washington State Highway Commission, the University contracted to implement a very comprehensive study of fuel-consumption and travel-time characteristics of commercial vehicles operating under controlled road conditions. The author again directed the work in cooperation with Professors Firey and W. C. Kieling of the Mechanical Engineering Department, who assisted in the instrumentation and pretesting. In addition, Professor D. E. Alexander of the General Engineering Department assisted in the supervision of the data collection, as did Professor H. M. Chittenden of the Civil Engineering Department, who also collected survey information.

In this test as many as 12 test vehicles were leased and operated under various conditions. These vehicles represented all of the truck and trailer, or combination types, of gasoline- and diesel-powered vehicles operating on the West Coast, as well as an urban gasoline-powered bus, an urban diesel-powered bus, and an inter-city diesel-powered bus. During the summer of 1959, nine University students with truck-driving experience served as test drivers and 12 engineering students worked as observers, collecting data and assisting in the analysis. The study was conducted 20 hours a day at least five days a week; it continued through the three summer months.

The study was devised to measure fuel consumption and travel-time characteristics of these vehicles operating under varying conditions of gross vehicle weight, speed, grade, surface type, and slowdown and stop cycles. The data was analyzed by use of the State Highway Department's IBM 650, and subsequent revisions to the data were perfected by use of the IBM 610 machine at the University.

The data from this study was compiled and presented to the Highway Research Board at its 39th Annual Meeting in Washington, D.C., in January, 1960. It is presently being printed in a separate Highway Research Board Bulletin No. 276, and will be combined with data on smaller-unit vehicles being assembled in a Bureau of Public Roads study. Also included in the bulletin will be the analysis of the data collected for the Bureau during the summer of 1958.

The information collected from this study has been of widespread interest and has been the subject of reports and discussions to many professional societies. The Bureau of Public Roads negotiated for an additional research investigation still in progress.

In the summer of 1960 a study was made of the fuel and travel-time characteristics of these commercial vehicles operating up and down various conditions of highway grade. The primary purpose of this project was to permit the prediction of fuel and travel time to be expected in going from Point A to B on the basis of the amount the vehicle rises or falls in elevation in traversing the route.

In the summer of 1961 the 1960 contract is to be extended for an additional period of time to include additional test vehicles and at the same time, under an additional contract, collect supplemental information regarding deceleration and acceleration as well as rolling resistance of these commercial vehicles.

The sum appropriated for these research studies since 1958 through July of 1961 amounts to $109,430.

R. B. SAWHILL,
Associate Professor of Civil Engineering

Structural Research

As generally understood, structural research comprises the investigation of the properties of parts and assemblies, and sometimes of whole structures. This includes theoretical analysis, model experiments, and tests in the laboratory or in the field. Scientifically trained engineering personnel, engineering helpers, and intricate and expensive instrumentation are the necessities for successful structural-research activity. At Washington these have only gradually become available as the Civil Engineering Department grew.

The early 1940's marked the turning point for modern structural research in the Department. We can say "turning point" because publications from the early 1920's through the 1930's are witness of intensive theoretical research activity in the field of structures. Some of these, such as the work of Professor A. L. Miller on moment equations and that of Professor S. Sergev on the buckling of two-story columns, still are sought-after reference papers. Other notable later work included that of Professor C. W. Harris, who supervised laboratory and design work on the Hell's Gate Fishway, Fraser River, B.C.,

at that time the largest undertaking of its kind in the world. A more complete turn to experimental research was brought about by two momentous events.

The spectacular failure of the first Tacoma Narrows Bridge in 1940 prompted the start of a research program on the aerodynamic behavior of suspension bridges. This program, under the leadership of Professor F. B. Farquharson, spanned more than a decade and became known and highly praised the world over. Many people learned about the existence of a university in Seattle for the first time through reports on this famous research project in the technical literature. The sectional-model method then developed is still widely used, and the reports published are among the most important sources of information about suspension bridges.

The completion of the building for a structural research laboratory and the erection of the giant testing machine (2,400,000-lb capacity) in 1942 assured a place for the department among the five best-equipped ones in the nation. The constant addition of up-to-date equipment, such as electronic instruments for measuring static and dynamic strains and machines for fatigue and impact testing, maintained the laboratory's outstanding position.

The impact of these improvements was reflected in undergraduate teaching, and through the extension of the graduate program in the field of structures. The laboratory was soon busy with sponsored research. The Ship Structure Committee of the Navy Department sponsored research on the welded reinforcements of openings in structural steel members, a project extending through five years. The Research Council on Riveted and Bolted Structural Joints of the Engineering Foundations and the Washington State Council on Highway Research sponsored a project spanning almost nine years on the behavior of joints made with high-tensile bolts.

The results of these experimental projects of Professors R. A. Hechtman and the author received national recognition through their publications, and some have been used in formulating the latest specifications on high-tensile bolts.

The most recent major project, on riveted plate girders with thin webs, was sponsored by the Bureau of Public Roads and the Washington State Department of Highways. It spanned a period of two years. The picture on this page shows the test setup, with the specimen 56 ft. long and 72 in. deep, in the 2,400,000-lb machine, ready for testing.

The Structural Laboratory is, of course, suitable for tests of timber and of reinforced concrete. A complete concrete laboratory with a prestressing facility was recently added, as planned by Professor H. P. Mittet. Facilities for dynamic testing are another recent addition to the Laboratory.

TEST SETUP FOR THIN-WEB PLATE GIRDER

The volume and the technical value of the research produced in the Laboratory would not be enough justification for such facilities in the College unless it also made a definite contribution to education. In connection with the three major research projects cited in preceding paragraphs 15 graduate students wrote their theses, some of which have been developed into publications in technical journals.

The availability of excellent research facilities not only attracts big-scale sponsored research, but also inspires continuous research activity on a small scale. The latter sometimes involves sponsorship by the Engineering Experiment Station or local industries. Aside from the immediate educational value of such small-scale research, the publications that often result are proof of a more than local significance. The laboratory is a great help to the industries of the area, since without it some of the needed test facilities would not be available within several thousands of miles.

D. D. VASARHELYI,
Professor of Civil Engineering

Mechanical Engineering

B. T. McMinn, *Executive Officer*

During the past five years, the graduate program in the Department of Mechanical Engineering has grown substantially, in terms of both the student enrollment and the research activity within the Department. Research projects currently under way include studies of forced-convection and free-convection heat transfer and boiling-heat transfer with high acceleration. Studies are also under way on a wide variety of stress-analysis problems, including one being done jointly with the School of Mineral Engineering on the effect of stress upon the microstructure of materials. In addition, a number of fluid-flow problems are being investigated. These include problems in jet mixing, flow separation in rocket nozzles, flow characteristics in the base region of a suddenly expanded supersonic stream, flow in vortex tubes, and two-phase flow. Another project involves a study of the process of engine-knock in gasoline engines.

In the area of instrumentation and control, projects include servomechanism analysis, process-control simulation, and computer application. In manufacturing processes, work is being done on flame straightening of damaged steel structures, the use of olivine sand for molds in foundries, the effect of tensile prestressing parallel to welds on the warpage of sheet-metal gage steel, and the evaluation of machining parameters in the metal-machining process. Brief descriptions of some of the projects are given in the sections that follow.

Fringe and Thickness Effects in Birefringent Coating

With the development of plastics having low moduli and high optical sensitivities, photoelectric analysis using birefringent coatings has become an accepted tool of experimental stress analysis for measuring surface strains in opaque bodies. Recently, the possible inaccuracy in the surface strain determined by birefringent coating analysis has been the subject of investigations. These inaccuracies, referred to as "thickness effect," are caused by the finite thickness of the birefringent coating; they result in at least the following four effects: (1) reinforcing effect due to the rigidity of birefringent coating; (2) differential-deformation effect caused by the differences in Poisson's ratios between the birefringent coating and the model; (3) variable-strain effect through the coating thickness in regions of high strain gradients; and (4) variable-strain effect through the coating thickness in regions of large curvatures of the specimen.

Obviously the magnitude of these four inaccuracies in birefringent coating analysis can be reduced by decreasing the thickness of the coating. Unfortunately, this reduction also decreases the birefringent response of the coating, and as a net result the experimental accuracy of birefringent coating analysis decreases further.

Under a grant from NSF, an investigation has been conducted on methods of improving the accuracy of analysis in a thin birefringent coating by using fringe multiplication, a technique in which the optical path through the birefringent material is increased without increasing the thickness of the material, thus effectively creating a coating of higher optical sensitivity.

Fringe Multiplication

When a fringe-multiplication mirror (a partially silvered mirror) is placed in the path of a light beam projected onto a back-silvered birefringent coating, the reflected light from the coating will again be reflected back onto the coating. This reflection occurs many times in succession, thus increasing the optical path and hence the birefringence without increase of the actual thickness of the coating. In order to isolate the multi-reflected light according to the number of reflections, the fringe-multiplication mirror should be obliquely inclined so that the multi-reflected light will be projected in directions of progressively increasing inclinations. A focussing lens that collects these obliquely inclined light beams onto a screen will then produce a succession of focal points. By placing an image-isolation aperture at this focal plane, any particular image of a multi-reflected light can be isolated for projection on an observation screen.

Thickness Effect

Although analysis of birefringent coatings is a whole-field method of analyzing strains, in many cases the coating is not bonded over the entire surface of a structure to be analyzed, but instead is bonded to small, limited areas of the structure. When the structure is loaded, a strain field is generated in the coating by the surface strains that are transferred to the coating. Assuming perfect bonding between the coating and structure interface, these interface strains in the coating will be identical to the surface strains in the structure. The strains in the coating will, in general, vary throughout the coating thickness except for certain plane-stress problems. Therefore the birefringence observed in the coating will not, in general, represent the true surface strains of the structure unless such strain variations through-

out the coating thickness are considered and corrected for. This variation in strain gradient was analyzed by Duffy *et al* for cases of one-dimensional and axisymmetric two-dimensional variations of displacements at the interface of the coating of a specimen. Duffy also derived the correction factors that compensate for these two effects, strain gradients, and curvature effects; and his results were utilized in this investigation.

Experimental Procedures

Description of Equipment. The reflection polariscope used here (as shown in the figure) has the conventional parallel-light design with an additional optical system for fringe multiplication. The large loss in intensity of the reflected light made necessary the use of a bright light source. The light source used was a 1000-w, A-H6, mercury-arc lamp, which was air cooled during operation. The predominantly green spectrum was further filtered so that the wave length of most of the incident light was in the vicinity of 5461 Å.

THE REFLECTION POLARISCOPE

The beam splitter was a half mirror of 50% reflectivity, and the fringe-multiplication mirror was of 70% reflectivity, this particular reflectivity being optimum for use in six or eight multiplications. All nonreflective surfaces of the mirrors were coated for anti-reflections in order to reduce the intensities of extraneous reflections.

Birefringent Coating. The birefringent coating used in this experiment was a commercially available Photostress, Type S coating with a strain-optical constant of $K = 0.1$ (according to the manufacturer's datum). The thickness of the coating was 0.120 in. Thinner coatings of thicknesses 0.072 and 0.048 in. were also used, but unfortunately the mirrored surfaces of available coatings were too irregular for fringe multiplication to be successfully employed here.

Specimen. The problem chosen to demonstrate fringe multiplication and thickness effect was a plate that had a central circular hole and was kept under uniaxial tension. The ratio of the hole diameter to the plate width was 1:2, where Howland's analytical solution exists. Coatings were bonded on both major surfaces of the plate to reduce any questionable bending effect due to the reinforcement by birefringent coatings. A strip of coating was also attached along one edge of the specimen.

Conclusions

These conclusions resulted from the investigation:

1. Fringe multiplication can be successfully applied to increase the accuracy of analysis of birefringent coatings.
2. The success of fringe multiplication depends on the quality of the mirrored surface on the birefringent coating.
3. When fringe multiplication is used in the analysis of a birefringent coating, the region of multiplication must be limited to the flat portion of the surface.
4. As has been mentioned, the correction factors for curvature and strain gradients derived by Duffy will increase the accuracy of the experimental results.

E. E. DAY,
Professor of Mechanical Engineering
and
A. S. KOBAYASHI,
Associate Professor of Mechanical Engineering

Olivine-Aggregate Molding Sands

Olivine, a mineral rock composed chiefly of magnesium silicate (90%), is found in extensive high-grade deposits in the Cascade Mountains of Washington. For the past several years Professors G. S. Schaller, W. A. Snyder, and others have been investigating the use of olivine as an aggregate in synthetic molding sands for foundries.

Olivine sand offers many advantages over the silica sands normally used for molds in foundries. First, the foundry health hazard is greatly reduced because olivine does not cause silicosis as silica dust may. Second, olivine has a much longer useful life in the foundry and leads to better quality castings than silica because of its lower coefficient of thermal expansion and the more uniform rate of change of the coefficient with temperature. The sudden expansion

of silica at 1000° F causes many types of surface defects and results in shattering many of the individual grains of silica so that they are no longer useful. Third, olivine does not react chemically with manganese in manganese steels, as does silica, thereby eliminating a very costly cleaning procedure for the castings. Additional advantages of olivine include greater mold strength owing to the angular shape of the grains and simpler control of molding properties because of the smaller number of ingredients required.

Currently, an attempt is being made to develop an accurate method of testing commercially produced olivine for chemically combined moisture. This moisture can cause steam problems in low permeability molds, such as investment molds. The ignition-loss test now being used is not valid because of oxidation of the olivine. This work involves the determination of the optimum operating temperature and heating time for removal of combined moisture. Equipment requirements are minimal, consisting of a high-temperature controlled-atmosphere tube furnace (shown in the figure) and an analytical chain balance.

THE TUBE FURNACE USED IN DETERMINING REQUIREMENTS FOR REMOVING MOISTURE FROM OLIVINE

In addition, an attempt is being made to determine the temperature at which the reversible reaction magnesium silicate + moisture→serpentine + magnesium hydroxide occurs at atmospheric pressure. This reaction constitutes a slow deterioration of olivine exposed to moisture, called weathering. The reaction temperatures are apparently unknown, and knowledge of them would be valuable in establishing procedures for minimizing deterioration of olivine during use. The effect on the reaction of impurities, such as the iron orthosilicate normally found in olivine, will also be studied.

The use of olivine aggregate bonded with ethyl silicate for making molds for precision metal castings is also being investigated. This work includes a study of the chemical reactions and their effects at the interface between ethyl-silicate bonded olivine and sodium-silicate bonded olivine. If satisfactory bonding of mold aggregates can be accomplished, a substantial increase in the production of large precision ferrous castings may be possible. Production is currently limited by the excessive costs of mold material.

P. W. FORD,
Assistant Professor of Mechanical Engineering

Flame Straightening of Steel

Steel structures frequently suffer damage from accidents, such as fire and impact, that are not reasonably a part of the original design considerations. Such assemblies can be rehabilitated by application of flame-straightening methods such as the ones developed by Joseph Holt of Seattle. Very attractive savings over replacement are realized when these techniques are correctly utilized; for example, highway bridges have been repaired for 5% to 65% of the normal replacement costs. Unfortunately, people qualified to apply these techniques are very scarce.

Field data evaluated by engineering analysis are being compiled to furnish tables and calculation techniques to permit engineers to properly organize and supervise flame-bending repairs. In addition, such aids will permit the field engineer to evaluate dam-

FIRE-DAMAGED HANGAR MEMBERS IN THE PROCESS OF BEING STRAIGHTENED

age from unequal heating such as results from casting, heat treating, and welding. To check on the usefulness of the data being compiled, calculation procedures are being applied to unusual problems as they arise in the field. As consideration of these problems indicates a need for particular information in a given area, research is started in the laboratory.

The photograph shows fire damage that was repaired by flame straightening the trusses in place under load instead of replacing a multitude of warped members, the result being a saving of $1,200,000.

R. E. Holt,
Assistant Professor of Mechanical Engineering

Engine-Knock Research

The occurrence of knock in gasoline engines has long been an obstacle to the improvement of engine efficiency and consequently to better utilization of petroleum resources. Despite many years of active research, the basic process of knock remains incompletely understood today. The early successes with gasoline additions, such as tetraethyl lead, directed the bulk of research into a study of the chemical reactions leading to knock. As a consequence the physical processes of knock have been less thoroughly studied. Over the past several years, a program of research on the physical processes of knock has been under way in the Department of Mechanical Engineering at the University of Washington.

All investigators agree that knock occurs during combustion from an abrupt reaction of those portions of the gasoline-air mixture in the engine cylinder that have not yet been burned by the normal spark-ignited flame. Two basic theories of the abrupt reaction, proposed many years ago by various investigators in Europe and the United States, the autoignition theory and the detonation-wave theory, have survived the test of time.

The autoignition theory proposes that the abrupt reaction takes place essentially uniformly throughout the unburned mixture. According to the detonation-wave theory, the abrupt reaction takes place immediately behind a shock wave as it passes through the unburned mixture. The research effort at the University of Washington has been directed toward determining which one of these two theories appears to be the accurate description of the knock process.

If knock is a detonation wave, marked impact pressures must occur in the knocking mixture. If the process is due to autoignition, impact pressures will not occur in the knocking mixture itself, but will be produced by the autoignition process in those portions of the cylinder contents already burned by the normal flame. For an engine operated without spark ignition, impact pressures should not develop in the cylinder if the combustion process occurs throughout the cylinder as an autoignition process. However, impact pressures would be expected to develop if a detonation wave were present.

In order to determine which of these processes was occurring, a means was devised of detecting whether impact pressure was produced in a motor-driven engine, without spark ignition. To detect impact pressures, a special indicator was fitted into the test engine. The motion of a small steel beam on the indicator was recorded electrically. Only impact pressures are capable of moving the beam.

In the first series of experiments very strong impact pressures were found to occur within the knocking mixture when knock took place. This finding indicates that knock is a detonation wave. Subsequent experiments showed that the originating shock wave is generated by a relatively slow chemical reaction of the fuel-air mixture. Further investigations are being directed toward determining the shock-wave generating abilities of various types of gasoline and their response to such shock waves.

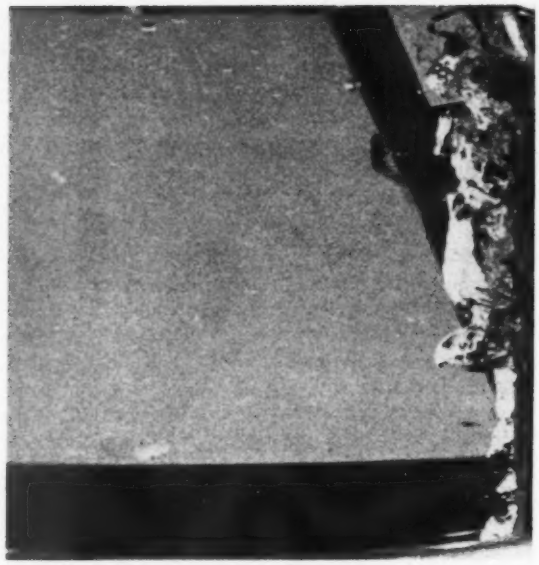
An improved understanding of gasoline-engine knock could aid in the development of engines capable of operating at high compression ratio, and hence high efficiency, without knock.

J. C. Firey,
Professor of Mechanical Engineering

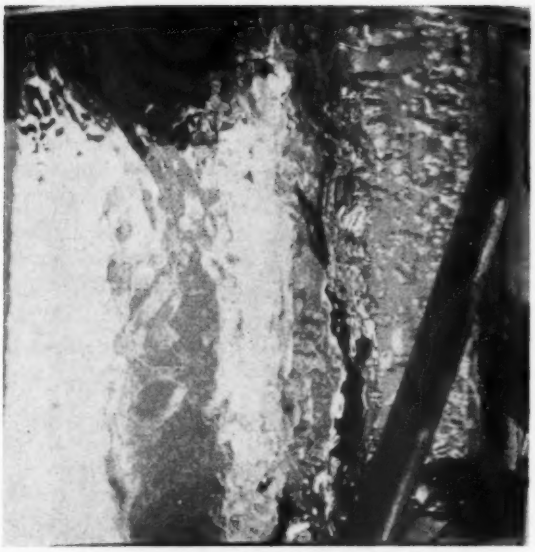
Boiling-Heat Transfer

The University has one of the most active programs in the country for studying effects of high acceleration on boiling-heat transfer. The problem is most important in obtaining a better understanding of the boiling process so as to take fullest advantage of its high heat-transfer efficiency. Recently, interest has grown in this project with the possibility of using high centrifugally created accelerations to replace the low-gravitational acceleration in outer space. Moreover, rockets and missiles in initial stages of flight experience high accelerations; knowledge of heat-transfer behavior under these circumstances is important. Work in this field at the University has been conducted under a grant from NSF.

Research into this problem at Washington has been concerned recently with the effect of acceleration on



VAPOR COALESCING DURING STATIONARY BOILING



VAPOR BUBBLES THROWN FROM HEATER SURFACE DURING ACCELERATION

the so-called "burnout" heat-transfer rate. When a surface is required to dispose of large amounts of energy by boiling, vapor liberated by the boiling process may insulate a portion of the surface. This causes local overheating, often to the point of melting the heater. The heat-transfer rate at which this occurs is sometimes referred to as the "burnout heat flux."

Results of the work done here show that centrifugally created high accelerations allow much higher heat-transfer rates to be attained before "burnout" occurs. Some idea of this may be gathered by reference to the two photographs. Vapor is shown coalescing on the heater surface during stationary boiling, whereas with acceleration imposed on the system the smaller vapor bubbles are sped away from the heat-transfer surface. With accelerations of 40 times the local acceleration of gravity, energy transfer rates of two and one half times the "burnout heat flux" obtainable with nonaccelerating conditions have been achieved.

Work is continuing in an attempt to derive an analytic approach to predicting "burnout heat flux" as a function of known system parameters. Experimental work is being conducted to determine the combined effects of acceleration, heater size, and heater orientation in fixing heat-transfer rates obtainable before "burnout."

C. P. COSTELLO,
Associate Professor of Mechanical Engineering

Studies of Forced-Convection Heat Transfer

Problems in forced-convection heat transfer are encountered in almost every phase of modern engineering practice. For instance, particularly interesting problems are encountered in the design of nuclear power plants or cooling systems for high-speed aircraft. Although extensive work has been done during recent years in the field of forced-convection heat transfer, many problems remain to be investigated.

Two forced-convection heat-transfer loops, one using liquid metal as the heat-transfer medium, the

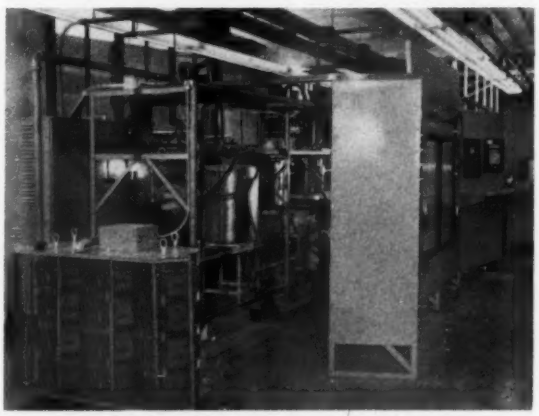


FIG. 1. SIDE VIEW OF THE WATER LOOP

other using pressurized water, have recently been put into operation at the University. These loops, which were built with funds from an AEC grant, are used for undergraduate and graduate heat-transfer laboratories and also serve as excellent facilities for graduate research.

Figure 1 shows a side view of the water loop. This loop consists of a pump that delivers up to 8 gpm through ¾-in. stainless-steel pipe to a 100-kw electrical preheater and to a test section 6 ft. long, where energy may be transferred at the rate of 120 kw. This energy is transferred to the flowing fluid by using the pipe wall itself as a resistance heater. A d-c generator at 80 v can supply 1500 amp. Following the test section, water-cooled heat exchangers reduce the temperature to 200° or less and return the fluid to the pump inlet to complete the circuit. Maximum discharge pressure of the pump is 350 psig.

The control and instrumentation panel for the water loop is shown in Fig. 2. From this panel the flow rate, pressure, and temperature of the water may be adjusted to desired values. The flow rate may be varied by controlling the speed of the pump; the pressure, by pump-speed control, pump by-passing, and needle-valve adjustment. The pressure decrease along the test section may be measured at small intervals by two banks of ten-tube well-type manometers. The temperature of the fluid and of the test-section walls are determined by some 50 thermocouples placed in appropriate positions in the apparatus. Temperatures are recorded by two self-balancing potentiometers, but at critical locations may be measured as well by a highly precise manually balanced potentiometer. The electrical power used is indicated by precision voltmeters and ammeters on the panel. The circulated water is mechanically filtered and deionized to keep its resistivity high. The conductivity may be monitored at the panel.

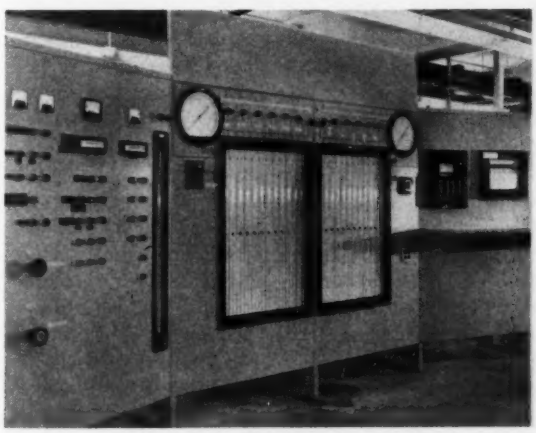


FIG. 2. CONTROL AND INSTRUMENTATION PANEL FOR THE WATER LOOP

The loop is designed so that various parts may be used separately. The motor-generator set has proven particularly useful in this respect, as the unit was designed so that the d-c power could be supplied to an external experiment and controlled from the panel.

Problems currently under investigation in the sodium-potassium liquid-metal loop include the effects of sodium-oxide concentration on film coefficients of heat transfer. The d-c power supply of the water loop has been used for the investigation of magnetic damping and boiling-burnout problems. Work on forced-convection local boiling and two-phase flow is planned for the immediate future.

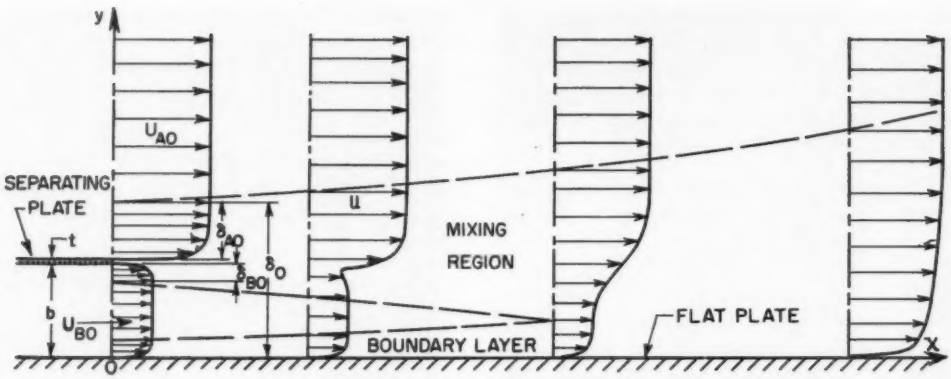
P. J. WAIBLER,
Professor of Mechanical Engineering

Turbulent Jet Mixing; Sudden Expansions in Supersonic Flow

Turbulent Jet Mixing: Initial Boundary-Layer Effects

Problems in turbulent jet mixing have been the subject of numerous investigations during the past three and one-half decades. Typical among these problems are the mixing of a free jet with an ambient fluid or the mixing between parallel free jets. Another problem of considerable interest is the mixing of a slot jet, confined on one side by a solid surface, with an external stream. The flow pattern for this case is shown in the figure. This problem is important because flow patterns of this type may be used to cool surfaces that might be subject to excessive heating by high-temperature external streams. Theoretical mixing solutions that allow the flow field in the mixing region to be predicted under various conditions of operation may be extremely useful in this or other cases, and considerable effort has been devoted toward obtaining suitable solutions.

Prior to about 1950, theoretical solutions were obtained for mixing problems in which initial boundary layer was negligible. During the past ten or twelve years, however, most of the mixing investigations have been aimed at obtaining solutions for problems in which the boundary layer immediately upstream of the mixing region could not be ignored. Notable



FLOW PATTERN FOR MIXING OF SLOT JET WITH AMBIENT STREAM

among this work has been that carried out by Korst and associates at the University of Illinois and the work of Pai and associates at the University of Maryland.

For the past three years investigations of mixing problems in which the effects of the initial boundary layer are significant have been under way at the University of Washington. Problems under consideration at the present time include (a) isothermal, two-dimensional, turbulent mixing between parallel free jets of the same fluid but of different velocity; (b) isothermal, two-dimensional, turbulent mixing between a slot jet, confined on one side by a solid surface, and an external stream; and (c) compressible mixing between a suddenly expanded supersonic stream and the fluid in the "deadwater" region downstream of the sudden expansion.

On the problems listed above, the most success to date has been attained with the problem of isothermal mixing between parallel free jets. In this work two separate methods of obtaining theoretical solutions have led to reasonably good agreement between theoretical and experimental results. Only limited success has been attained on the problem of mixing between a confined slot jet and an adjacent stream. Work in this important area is still under way.

Work on (c) is just a small part of a larger project involving the study of flow characteristics in the base region downstream of a suddenly expanded supersonic stream. In this work attempts are being made to measure velocity and total temperature profiles in the mixing region. The experimental results will be compared with approximate theoretical solutions presently available.

The work listed under (a) and to some extent that under (b) has been conducted under a grant from NSF. This support is gratefully acknowledged.

Flow in the Base Region of a Suddenly Expanded Supersonic Stream

When a supersonic stream flows past a body with a bluff base or past a sudden expansion in an internal flow channel, the base region downstream of the sudden expansion tends to be pumped out by the external stream. If the mass pumped out cannot be replaced, as is the case with confined regions, the pumping effect reduces the pressure in the base region, causing the external stream to expand toward the base region. Downstream from the sudden expansion, where the external stream interacts with the solid wall, a trailing shock occurs, producing a rise in pressure. If the base region is completely confined, the flow pattern adjusts in such a manner that the fluid entrained from the base region is unable to pass through the trailing shock and merely recirculates. If fluid is being injected into the region or being removed from it, the pressure in the region will be altered; but the circulation in the region will continue to take place, the exact pattern depending upon the method of injection.

Knowledge of the pressures that exist in such regions and of a means of predicting them are important since they have a substantial effect on the drag on bodies. Fortunately, there is by now a theoretical means of treating the base-pressure problem for a wide variety of practically important flow configurations, thanks to Korst. More recently the flow in the base region has been of interest in connection with the so-called "base-heating problem." For example, difficulty has been encountered on missiles with a cluster of rocket exhausts, with the problem of backflow of rocket exhaust gases into a base region great enough to cause burnout of the base. As the exhaust jets impinge upon each other and produce a trailing shock, some of the hot gases travelling at a low velocity in the mixing region are not able to penetrate the flow field downstream of the shock and must turn back

into the base region. The gases then escape from the base region through the openings between the nozzles. This process can produce extreme increases in temperature of the missile base. Knowledge of the flow characteristics in the base region is essential to a full understanding of this problem and to its solution. Here again Korst and associates, as well as others, have treated the problem theoretically with considerable success; however, many interesting phases of the subject remain to be investigated.

The general problem of flow in a base region is currently being investigated at the University. Initial work is being done with two-dimensional internal-flow channels. Although flows past a missile and past a sudden expansion in internal flow differ, they are similar enough in nature that the flow mechanism in the base region may be studied conveniently with internal-flow configurations. In the current investigation, flow characteristics in the mixing region between the external stream and the base region, as well as the flow in the base region itself, are being studied. Included in the investigation will be studies of flow patterns that occur with heated mass addition or with mass removal. Attempts are being made to measure velocity and total temperature profiles throughout the base region and the mixing region as well.

M. E. Childs,
Professor of Mechanical Engineering

Analogs and Computer Simulation

Some of the projects in instrumentation and control have produced analyses or experimental models that are usable directly in the classroom, in accord with the increasing recognition of the mathematical analogousness of subjects that appear physically to be quite different. An example is the relationship between control-system transfer functions and two-dimensional fluid flow. A recent project developed this analogy and also the membrane analog. The analysis is quite similar to that for electrostatic fields.

A "transfer function" is a complex function that, when multiplied by the Laplace transform of the input to a system, gives the transform of the system's response. It is commonly expressed as the ratio of two polynomials, generally having complex roots. A useful consideration is the "logarithmic transfer function," a complex quantity whose real part is the logarithim of the transfer function's magnitude, and whose imaginary part is its phase angle.

In fluid flow, the streamlines are loci of constant "stream function," and the curves orthogonal to the streamlines are loci of constant "velocity potential." These may be expressed as a single quantity, the "complex potential," whose real part is the velocity potential and whose imaginary part is the stream function.

By means of the basic properties of functions of a complex variable, this complex potential of fluid flow may be shown to be analogous to the logarithmic transfer function of control systems. In particular, flow sources can represent zeros (numerator roots) of the transfer function, and sinks can represent poles (denominator roots). A powerful procedure in control-system design is to sketch loci of constant transfer-function phase angle, and to conider the effect on these loci of introducing additional zeros and poles. The fluid-flow analogy visualizes this, since the corresponding effect is obtained on streamlines by introducing sources and sinks. An important characteristic of many control systems is "dead time," a time delay between input and response. This usually makes the system analysis considerably more complicated, but in the fluid-flow analogy it corresponds simply to the superposition of a uniform fluid velocity.

The project referred to developed these and other relationships. It showed that, since the height of a thin membrane under certain conditions obeys Laplace's equation, this height may be considered as the real or imaginary part of an analytic function of a complex variable, and in particular may represent the magnitude of the logarithmic transfer function, with interesting analogous properties similar to those of the fluid-flow representation of control systems.

Related projects have developed other analogies. A mechanical system was constructed to simulate the general linear second-order system, with step, ramp, or sinusoidal inputs. One of the difficulties encountered in such attempts is the problem of obtaining purely viscous damping; the system developed here is interesting in this regard because it employs a uniquely designed long-slotted electromagnet.

Computers are also valuable in simulating systems. A recent project used the digital computer to analyze time lags. For direct classroom application, another project developed an analog-computer representation of control systems, specifically arranged for very convenient variation of process parameters and control modes. Of general use is a project now under way to develop digital-computer problems suitable for many undergraduate courses in mechanical engineering. By such means we hope to further our students' appreciation of mathematical analysis and their recognition of the value of computers as engineering tools.

P. L. Balise,
Professor of Mechanical Engineering

School of Mineral Engineering

D. A. PIFER, *Director*

Problems are created in the mineral industries by the widely diverse nature of similar materials, and no amount of theoretical analysis can yet be substituted for thoroughgoing laboratory experimentation with materials; yet, in spite of the complex nature of the multitude of industrial materials, certain characteristics and internal structures exhibit similarity and give order to their properties. The development of a unified approach to the study of materials is characteristic of the academic growth in the School, and continued study of relations between properties and technologic conditions is a major function of the research being pursued by the faculty.

Since 1950, substantial support by industry and government agencies, especially the Boeing Company and the Atomic Energy Commission, has contributed to the research potential of the School. An insight into the varied nature of materials engineering and the approaches to their problems is afforded by the projects described in the following pages.

Although the School comprises three academic divisions—Metallurgical, Ceramic, and Mining Engineering—this review is presented from a unified viewpoint according to functions that involve all the divisions.

Resource Development

Contributions by the University to the development of the mineral resources in the Northwest is an activity of long standing. In addition to helping establish the local industrial base, the development of mineral wealth is essential to the economic well-being of the nation. The activities described in the following notes are some of the current work in this field.

Cooperative Research with the U.S. Bureau of Mines

Recent research supported jointly by the School of Mineral Engineering and the Seattle Research Station, U.S. Bureau of Mines, is in the fields of coal preparation and nonmetallic minerals. Current projects in coal preparation involve the dense-medium cyclone, hydraulic classification, and beneficiation of the coking coals of Pierce County.

A dense-medium cyclone pilot plant with a capacity of 10 tons per hr has been built to explore the possibility of utilizing this process to clean coal of a size down to 0. As conventionally used, material finer than about ½ mm must be screened out ahead of cyclones and treated separately by means of froth flotation. Therefore success of this project would reduce both the capital and operating costs of coal-preparation plants. Two principal problems must be overcome. The first of these is to hold the medium loss or consumption within economic limits, and the second is to maintain a medium of proper quality. The hydraulic-classification project is one phase of a continuing investigation of various liquid-solids separation processes that can be used to minimize the pollution of streams by effluents from coal-preparation plants. The present work involves the use of cyclone-type classifiers operating in tandem with screw-type units to provide inexpensive recovery of all solids coarser than about 200-mesh.

The coking coals of Pierce County can be used by the Japanese steel industry if properly beneficiated. Several years' research involving the application of various cleaning methods—both conventional and specially adapted—have led to a flowsheet that is feasible from both the technical and economic standpoints. This work has resulted in a contract to supply 800,000 tons of the coal to the Japanese steel industry.

The Bureau's nonmetallics laboratory is conducting research and resource studies of the mineral deposits located in Washington, Idaho, Oregon, and Montana. The resource investigations are made upon specific commodities to locate, test, and select the deposits most suitable for development to supply raw materials needed by industries of the area. Research is concentrated on methods of beneficiating and processing the raw materials.

Recently the qualities of four clay deposits in northeastern Washington and northern Idaho were investigated in detail. The results showed that the best deposits can be processed to yield high-quality raw materials needed by local industries, and established the best methods for beneficiating material from these deposits. Work on this project was instrumental in establishing a plant at Bovill, Idaho, for processing the clay to obtain silica for the glass industry and high-quality clay for the ceramic and paper industries of Washington. In another project, all known and some new deposits of massive quartz and silica sand were examined and tested for quality. This investigation aided in eliminating a critical shortage of silica needed for manufacture of silicon alloys and glass. Two deposits examined during this investigation have been developed and are now producing silica for industrial use in the State. Still other industrial minerals under investigation include halloysitic clays, nepheline syenites, chromite, and sillimanite minerals.

D. A. PIFER,
Professor of Mining Engineering

Iron-Ore Prospects

In the State of Washington the absence of a steel industry based on iron ores is frequently noted by civic and industrial groups. A basic steel industry requires resources of iron ore reasonably near the furnacing plant in adequate quantity to assure an economical operating life and quality sufficiently high to yield an acceptable product. Numerous iron-ore deposits have been reported in Washington, and some of them have been investigated during the period since World War I. Although these investigations have value, they have been limited in scope and have devoted little attention to detailed mineralogy or economic geology. This consideration impelled the Division of Mining Engineering recently to begin a systematic study of individual iron deposits located along the western Cascades. The author is directing the project, utilizing graduate and senior students.

Important factors contributing to the economic consideration of an iron deposit are the extent and grade of the deposit itself, the local geology that may influence the extension of the ore, and its mineralogic and chemical constitution. When an inspection of the site shows that a mineralized zone is worth study, the first step is to determine what is known about the area from existing geologic reports, maps, and records of production. This search is followed by field work during the summer or early autumn.

At the deposit, the work consists of mapping the geology immediately in the vicinity; proper sampling and measurement of outcrops; and determination of its extent by survey and by a geophysical reconnaisance. These studies are recorded on plans for which vertical sections are also given when feasible. Specimens are collected for laboratory identification of the rocks and minerals, including their textural relationships. This data, together with the field structure, enables the collector to form an opinion on the mode of origin of the deposit as well as some conclusions on possible extent. Measurements of grain size and determination of the ore minerals and their association are important preliminary steps for beneficiation or "up-grading." When a sufficiently important deposit is found, laboratory work on beneficiation may be started. The Blewett Pass ores have responded to such study, and the application of newer techniques may bring them as well as others nearer to becoming a base for additional industry.

Samples are assayed to find the iron content, but especially for sulphur and phosphorus, whose presence or absence are measures of ore quality. Resources do not allow extensive sampling, but enough is done to indicate the chemical character of the ores.

The results of these investigations are recorded in theses available in the University Library. The State Division of Mines and Geology makes a copy of these works, and the original is on open file for any mining company or person interested in mineral exploration. Studies to date include reports on iron deposits in three areas: Snoqualmie Pass, the North Bend, and the Middle Fork of the Skykomish. It is hoped that eventually all known significant occurrences of iron ore will be studied and reports made available.

D. L. ANDERSON,
Associate Professor of Mining Engineering

The Flotation of Chromite from Olivine

A research investigation on chromite ore was recently completed in the mineral-dressing laboratories by Evan A. Lowe under the author's direction. The purpose of the project was to investigate the use of flotation for separating chromite from olivine, a process that has not generally been applicable. Flotation is an application of surface-chemical principles that causes minerals in a water phase to be selectively coated with air-avid surfaces, so allowing them to be concentrated and separated at air-water interfaces. There are numerous deposits of chromite-bearing olivine in the Twin Sisters Mountain area of Northwestern Washington, the ores of which had previously resisted concentration by flotation; material from this area was used in the investigation.

Initial tests consisted of microscope examination of ore samples to determine the mineral association. The chromite occurs predominantly in the 0.5- to 0.6-mm size range. The matrix is essentially olivine, relatively free from alteration. Some fine chromite crystals occur, disseminated in coarser ones. A composite ore sample assayed 25.0% Cr_2O_3. Minerals were separated by means of the Franz magnetic separator and heavy liquids to determine the chemical and physical properties of the pure constituents. The pure chromite mineral contained 50.0% Cr_2O_3, as compared to the ideal value of 68%. The deviation was due to isomorphous substitution of aluminum for trivalent chromium.

A series of laboratory-scale flotation tests was then planned to assess important variables relative to the surface chemistry of the minerals in a flotation pulp. The results of these tests indicated a high degree of selectivity between the chromite and olivine. Final metallurgical results gave a recovery of 93.0% of the chromite in a concentrate assaying 47.41% Cr_2O_3 with a chromium-iron ratio of 2.32.

The investigation then was directed toward establishing the fundamental mechanisms that controlled the degree of selectivity. Such knowledge would be useful in handling similar mineral-separation problems. Test results indicated that the preflotation conditioning, which controlled the selective surface-chemical behavior of the minerals, could be divided into two steps: (1) preliminary conditioning to remove collector-consuming ions from solution and render both the chromite and olivine surfaces air-avid, and (2) additional chemical conditioning to produce a water-avid surface on the olivine mineral only.

In step 1 the chromite became coated with chromium oleate reinforced by a neutral hydrocarbon, and the olivine with magnesium and iron oleate, also reinforced by the neutral hydrocarbon. Testing indicated that the fluoride ion was necessary to precipitate Fe and Mg ions from solution that would otherwise have formed metal oleates, depleting the solution of the oleate collector ion. After this step, selectivity would not be achieved as both surfaces were hydrophobic. However, in the second stage an increased hydrogen-ion content rendered the surfaces of the olivine more mobile; thus they were unable to support an oleate collector coating. In this way the chromite surfaces only were rendered air-avid and ready to concentrate at an air-water interface.

The neutral hydrocarbon played another role. It produced an excellent sorting froth that minimized the mechanical entrainment of slimed olivine particles into the chromite concentrate. Evidence indicated that the neutral hydrocarbon probably reduced the adsorption of the oleic acid molecules at the air-water interfaces, thus reducing its frothing effect.

The investigation developed a selective technique for chromite flotation and made a contribution to the understanding of reagent functions in nonmetallic flotation.

F. B. Brien,
Associate Professor of Mineral Engineering

More Reactive Pozzolan Cements

The use of pozzolanic silicates and glasses as chemical buffering agents in concretes exposed to alkali and sulfate salts illustrates how readily available raw materials and ancient techniques can be combined to meet critical demands. The price we pay for ever-higher strength in today's portland cements is unwanted calcium hydroxide released during hydration, for our cements are composed of high percentages of tricalcium silicates and aluminates. Such freed lime contributes a little to concrete strength, but combines with salts to form expansive, unstable compounds under certain conditions of use. By replacing some of the portland cement with lime-reactive silicates and aluminates, such excess lime is inactivated or mopped up to form stable, insoluble compounds. Some pozzolans have the additional ability to inhibit expansive reactions between alkalies and reactive silica after the concrete has set. Their use will often also improve concrete workabiltiy and density, lower the heat of hydration and effect cost savings.

Research has been directed at determining the extent to which pozzolans can be used for specific corrective purposes with portland-cement concretes. The writer's investigations have sought to find processing conditions and techniques for achieving maximum reactivity in these materials, and particularly to find ways to accelerate the relatively slow lime-pozzolan reaction with catalysts, seeds, and chemical activators. Basic research is being suggested and supervised in line with students' thesis work in ceramic engineering.

All kinds of pozzolanic raw materials must be processed by one or more stages of grinding and classifying, as well as by heat or chemical activation, to bring out their optimum lime or alkali-reactive and hydraulic powers. Many such materials are available in the Pacific Northwest. As their beneficial effects become more widely appreciated and demanded in the construction industries, their increased use should lead to a definite pozzolan industry.

Basic and applied research into the mechanism of the lime-silicate pozzolanic reactions may soon point to a way in which this reaction can be speeded up. We should then be able to produce pozzolans from raw materials that can be compounded with lime and accelerators to equal portland cements in hydraulic activity, thus opening new marketing potentials. Already it has been possible with some of these materials and techniques to produce lime pozzolan cements for masonry use, stuccos, steam-cured concrete products, oil-well cements, and soil cements without recourse to blends with portland cements. Even without such a development, pozzolans are being used and specified more and more as a portland-cement admixture in general usage, rather than solely for specialized chemically buffered concretes as heretofore. Thus within the concepts of modern cement and concrete technology we are striving to find scientific basis and understanding in an ancient art.

W. G. Bauer,
Lecturer in Ceramic Engineering

Materials Research

The principal research effort of the faculty is centered on various fundamental aspects of materials, with the object of creating a better understanding of the relation between structure and properties. The successful use of materials depends on their response to the conditions imposed upon them; hence a sound understanding of their basic nature, the internal forces and structures that differentiate them from one another, is essential to all sophisticated applications. The following brief descriptions tell of some of the projects now being followed in the laboratories in Milnor Roberts Hall. The first two describe studies of changes in crystal structure and composition in the solid state; the next three, effects related to mechanical work on materials as reflected in deformation and microstructures; and the last group of three, current studies of surface phenomena and their industrial significance.

SOLID-STATE REACTIONS

Considering the various properties of the multitude of materials that the modern engineer has at his disposal, one property stands out against nearly all the others; most of them are solid. Although to all outward appearances solids appear quite stable, the materials engineer knows that the microstructure of most of these materials will control the stability of the solid. To be obtained in a useful engineering form, then, they must be processed according to rigid standards to assure the obtaining of the desired structure. To determine these standards, a thorough knowledge of the reactions taking place during fabrication and under various extreme environmental conditions is necessary.

These reactions, classified as solid-state reactions, are the subject of several basic research programs in the ceramic and metallurgy divisions.

Phase-Transformation Studies

Several of the research projects under way in metallurgical engineering are studies of the internal structure of alloys and how temperature affects it. In this research, called "phase transformations in solids," the investigations are primarily concerned with the atomic processes and the rates of solid-state reactions. To use effectively materials that may be unstable above room temperature, an understanding of the mechanism of fundamental atom migrations is necessary. In effect, these studies are concerned with the processes in which the internal structure is modified in going from an unstable to a more stable condition.

In a project directed by D. H. Polonis, Associate Professor of Metallurgy, under the sponsorship of the AEC, a study is being made of the effects of alloy composition and temperature on the decomposition of metastable phases. One aspect of this program involves alloys of the titanium-copper system in which the rates and mechanisms of tempering are under investigation. Titanium-copper alloys (0-10% copper) undergo a martensitic or diffusionless shear-type transformation during quenching. This transformation is similar in principle to that involved in the hardening of quenched steels. The martensitic transformation produces a highly imperfect and unstable internal structure that tends to decompose and to form more stable products during tempering. The tempering reaction is accompanied by measurable changes in physical and mechanical properties. This research has shown that the electrical resistance and microhardness of the martensitic alloys are profoundly affected by tempering. Studies are under way to utilize such measurements to follow the kinetics or rate of the solid-state reactions that occur. The structural changes accompanying the decomposition of the martensitic phase are being studied by means of x-ray diffraction and microscopy. Special experimental techniques have been developed for treating and studying the alloys in this work. For example, a special furnace has been constructed to enable heat treatment in vacuo or in argon gas at temperatures up to 1100° C, with provision for subsequent rapid quenching.

In another project, conducted under a NSF grant and under Professor Polonis' direction, the precipita-

MEASURING THE CHANGE IN ELECTRICAL CONDUCTIVITY OF A CERAMIC TEST PIECE AS THE TEMPERATURE RISES

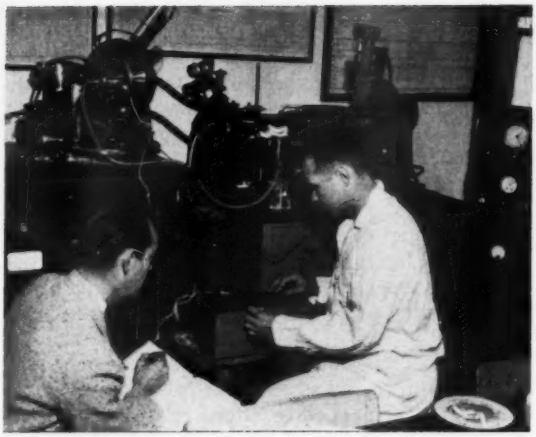
tion reactions of retained high-temperature phases in copper-silicon alloys are being studied. Quenching of alloys containing approximately 5% silicon results in retention of the high-temperature phase with an excess of silicon atoms dissolved in the copper structure. During subsequent heating at temperature below 550° C, the silicon atoms should migrate in order to produce a more stable arrangement. The work has indicated that the reaction involves several distinct stages, depending on the temperature at which aging treatments are conducted. In this work the reaction mechanisms are being studied primarily by means of rotating and oscillating crystal x-ray method. Analysis of the positions and shapes of x-ray reflections provide information about the nature of the atomic movements and details about the changes in the internal structure of the alloys. As in the AEC project, this one has the long-range objective of advancing our understanding of nucleation and growth reactions in solids.

In the Ceramic Engineering Division, two studies on phase reactions and transformations are directed by the author. The first of these is concerned with detecting phase transformations, such as a change from one crystal structure to another, or the dehydration or decomposition of a ceramic body while being heated, by means of a change in their electrical resistivity. The differential thermal-analysis technique, in which the heat of transformation or reaction is measured during the heating process, is widely used; however, it suffers on two counts. First, the temperature at which the reaction is detected depends on the heating rate; and, second, it cannot detect reactions having low heats of reaction.

This new technique, which depends on a measurement affected by the actual crystal bonds, should overcome these difficulties. That is, as a crystal transformation occurs, bonds are broken, ions rearranged, and bonds re-formed. During the transition period the electrical resistivity changes markedly; moreover, the actual resistivity of the two species is usually different, since it depends to some extent on structure. The temperature at which this change in resistivity occurs can also be readily determined.

Special experimental techniques have had to be developed for applying ohmic contacts to these oxide materials and for measuring resistances up to 10^{14} ohm-cm at temperatures up to 1000° C.

Not only does this program give us a new analytical tool, but the techniques and measurements involved also lead into other studies on the semiconductive properties of ceramics, contact potentials, work functions, and other basic parameters involving the electronic structure of these compounds.



CHECKING THE TEMPERATURE OF A SPECIMEN IN A HIGH-TEMPERATURE GONIOMETER ATTACHMENT FOR THE X-RAY DIFFRACTION UNIT

The other study is concerned with examining the phase reactions that occur in the alumina (Al_2O_3) - zirconia (ZrO_2) system. Both of these oxides are commonly used refractory materials with melting points of 2040° C and 2700° C respectively; however, the binary-phase diagram has never been determined. Pure alumina is usable up to 1950° C and pure zirconia up to 2500° C; but in contact with each other 1750° C is a maximum stability limit. This limitation has long been recognized, but the exact nature of the reaction that occurs at 1750 - 1800° C is not understood. The alumina disappears; the zirconia changes color from light yellow to orange and becomes very porous. Apparently a volatile compound is formed, and this reaction proceeds at a very rapid rate. By determining the nature of the reaction, the reaction products, and the reaction rate, we may be able to select additives for the system that will slow down or prevent the reaction from occurring.

A small oxygen-acetylene fired furnace that can attain temperatures in excess of 2400° C in less than one hour has been constructed. The largest problem faced has been what to use as a container for the samples being reacted, as zirconia is about the only material sufficiently refractory for these temperatures. A piece of iridium foil (mp 2400° C) being tried may solve this problem.

This particular problem is but one of many being encountered in high-temperature phase reactions. Its solution will not only be of immediate practical importance, but also give an insight into the fundamental processes occurring in many similar instances.

C. E. McNEILLY,
Assistant Professor of Ceramic Engineering

Order-Disorder Changes

The most common simplifying assumption made in considering the distribution of atom types in metallic solid solutions is that a random dispersion exists. This means that on a statistical scale the numbers of, say, atoms of A and atoms of B in an average microvolume of a binary alloy are in the same proportion as that given by the chemical analysis of the overall alloy. On an atomic scale this would automatically indicate that a particular atom of component A is completely indifferent to the nature of its surrounding atoms; that is, it is disordered.

Experimental evidence, such as that obtained from particular phase diagrams, from microstructural observations, and from the fact that such things as intermetallic phases exist, points up the more common behavior of atoms in mixtures or combinations. From this we conclude that atomic interaction is a major effect in most atomic mixtures and, adding our increasing knowledge of such details as atom clustering, we can extrapolate our thinking far enough to say we doubt that any alloy exists whose structure is completely disordered.

There are, however, alloy systems whose magnitude of disorder even at low temperatures is very large, and this disorder is increased as the temperature increases. Systems showing a high degree of disorder are not particularly common. Most alloy systems show a certain measure of short-range order that also is usually decreased at high temperatures. The extreme instances of this more common case are shown at particular compositions in certain systems. In these alloys one can observe a change from the short-range ordered condition (where one finds in a binary alloy mixture a tendency for the A atoms to surround themselves with B atoms and vice versa) to long-range order, in which each atom has as its near neighbors only atoms of the opposite type. This change from short- to long-range order occurs with a decreasing temperature, either gradually (second-order reaction) or discontinuously (first-order reaction).

In some of these alloys the reaction, on passing through a critical temperature, seems to occur almost instantaneously, regardless of the cooling rate. Other alloys undergo a more sluggish transition and the high-temperature disordered condition can be retained by rapid cooling. The long-range ordering of such alloys can be allowed to progress under controlled conditions such as isothermal annealing below the critical temperature. The author is directing an investigation of this kind of alloy.

The ordering reaction is frequently accompanied by sizable changes in the thermodynamic properties of the alloy; and the state of the system influences the electrical, mechanical, and magnetic properties. The dependence of the physical properties on the structural arrangement of such systems makes possible a study of the ordering kinetics by following the changes in a specific property.

While the end objective of this work is best called fundamental research, certain practical implications may develop. For example, in some systems very interesting magnetic properties result concomitantly with the long-range ordering reaction.

E. C. Roberts,
Professor of Metallurgical Engineering

Photomicrographs Showing a Sequential Development of Grain-Boundary Recrystallization in a Quenched Martensitic Structure of a 50-50 Nickel-Manganese Alloy

DEFORMATION AND MICROSTRUCTURE

Qualities, such as fracture strength, plasticity, and resistivity, that are affected greatly by the structure of crystalline materials are termed structure-sensitive properties. In this sense, *structure* refers mainly to the irregularities known as "defects" in the otherwise periodic arrangement of atoms. These defects may be large scale, like surface boundaries, or smaller scale, like crystal boundaries, dislocations, vacancies, impurity atoms, and phonons. An understanding of what these defects are and how they affect the solid will allow some measure of control of the structure-sensitive properties.

Of particular importance in engineering applications are the mechanical properties of solids. To what degree are they elastic; will they deform plastically or will they fracture under increased loads; what effect does environment (temperature, atmosphere, etc.) have on their properties? The following descriptions recount some current research into these questions.

High-Temperature Microscopy

A major barrier to progress in the application of engineering materials is the shortage of a fundamental understanding of their properties at elevated temperatures. Until a short time ago, microstructural studies could be done only at room temperature. Now, however, high-temperature microscopy has become a major tool that opens new vistas in materials research. A recent paper in *Trend* (Jan., 1961) outlined a project undertaken by the writer, in which the high-temperature microscope is being used to determine the constitution of alloys at elevated temperatures and to study reactions that occur as a result of temperature change.

Current studies involve copper-rich alloys of copper and silicon, which are known to undergo transitional phase formation during aging that follows cooling from temperatures in excess of 700° C. We have now been able to observe the actual growth of the transitional phase at high temperature by means of the hot-stage technique. These results provide a direct confirmation of deductions based on x-ray diffraction studies made on the same alloys at room temperature after heat treatment.

A project, supported by the Boeing Company and directed by the author and Raymond Taggart, Assistant Professor of Mechanical Engineering, is applying the high-temperature metallographic technique to deformation studies. The effects of microstructure and state of stress on both micro deformation and the initiation and propagation of fracture will be studied. These matters are important in reducing failure by fabricated materials.

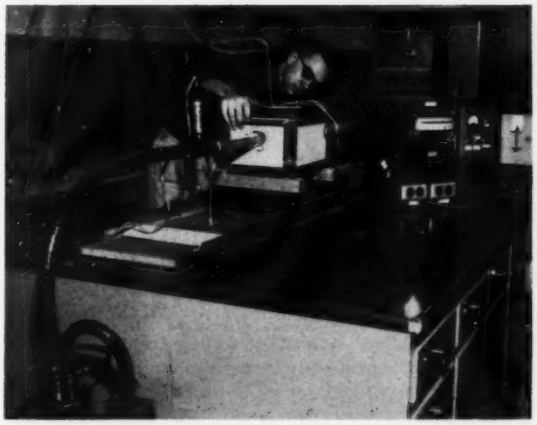
SETTING UP HOUNSFIELD TENSOMETER FOR STUDY OF PLASTIC DEFORMATION IN HIGH-PURITY METALS

In this project a special attachment is being designed to apply forces to metal specimens while they are being observed under the microscope. This equipment will permit the simultaneous heating of specimens so that the behavior of individual crystals under load at elevated temperatures can be observed. Studies of this type are expected to contribute a better understanding of the mechanism of material failure and a greater appreciation for the limitations imposed on materials by extreme environmental conditions. When such limitations can be specified, a major contribution to safety as well as to efficiency will have been achieved.

D. H. POLONIS,
Associate Professor of Ceramic Engineering

Deformation Mechanisms

Either plastic deformation or brittle failure under excessive loading limits the usefulness of a material in many applications. Prevention of some failures, such as the splitting of ships at sea or the midair bursting of the unfortunate "comet" planes, will be easier and more reliable if we understand the details of the deformation process and the origin of self-propagating cracks in solids. This understanding centers around the behavior of various types of dislocation defects in crystalline solids: the ease of movement of these dislocations is a measure of duc-



OPERATING THE FURNACE USED FOR THE MODIFIED BRIDGEMAN TECHNIQUE OF GROWING SINGLE CRYSTALS

ADJUSTING THE FURNACE ON THE HIGH-TEMPERATURE METALLOGRAPH

tility, and things that impede motion increase the tendency to brittle failure.

Two research programs directed by the author are concerned with the mechanisms of deformation and with an answer to the question of what plausible combination of atom movements explains the observed phenomenon of deformation.

In the first program, sponsored by the Transport Division of the Boeing Company, the interaction of solute atoms with dislocation is being studied to gain insight into the nature of flow stress in solids. The diffusion of these solute atoms is enhanced by the production of vacancy defects (unfilled sites in the crystal) during dislocation movement. This in turn may accentuate the interaction and further hinder dislocation movement. Knowledge of the details of this interaction will enable us to better control crack propagation (by controlling ductility), particularly under cyclic loading.

In the second program, the mechanism of twinning is being investigated to help explain the origin of micro-cracks leading to brittle failure in solids. The twinned regions form extremely fast and exert high local pressures on the surrounding structure. If sufficient deformation cannot occur to relieve this pressure before cracks are initiated, brittle failure may occur. Low temperature and high rates of deformation (e.g., explosions) lead to such situations. An understanding of the detailed atom movements may enable us to control the occurrence of twinning and thereby allow us to engineer safer structures.

W. F. FLANAGAN,
Assistant Professor of Metallurgical Engineering

Determining High-Temperature Changes in Materials

Changes in the modulus of elasticity of materials with changes of temperature affect the design of equipment to be stressed at high temperatures. The conventional determination of an elastic modulus always presents problems of accurate measurement of displacement under stress. The deflections are usually small so that delicate, very precise equipment is required. These delicate measuring devices cannot be exposed to high temperatures; and remote sensing extensions, added to these devices, cause manipulative difficulties and loss of precision.

A different approach to the measurement utilizes the fact that all materials sufficiently rigid to form a solid piece can be made to vibrate. The natural frequency of vibration is a function of the physical dimensions and the modulus of elasticity. The application of this relation to determination of the elastic modulus involves measurement of the natural resonance frequency of a bar supported in a particular fashion, and evaluation of a constant factor, M. In general, dimensional changes are small and Poisson's ratio is considered constant over moderate temperature ranges. Thus one may say that the elastic modulus is proportional to the natural frequency of vibration for any one material.

Several investigators have studied this method, utilizing various means for exciting vibrations in the test piece and using both auditory and electrical

methods of frequency determination. Nearly all of these methods have presented difficulties in coupling the exciter and the measuring device to the test piece without affecting its natural frequency of vibration.

An apparatus being developed by the author excites the test piece by means of a vibrating air column. Vibrations induced in the test bar are detected by changes in the amount of light reflected to a photocell. By using the lower end of the bar as a reflector, the focused image of a light source moves across an aperture in front of a photocell. The moving light beam then causes the current flowing through the photocell to fluctuate in sympathy with the vibration of the test piece.

The actual resonant frequency is finally determined by comparing the frequency of the exciter with that of the variation of the photocell current. This comparison is made by display of Lissajous figures on an oscilloscope. Thus very accurate determinations of resonant frequency may be made and used as a basis for calculating the elastic modulus.

The determination of elastic modulus by the resonance method includes a calculation that in addition to the resonant frequency also involves values for length and thickness of the test specimen. Therefore for exact measurements one must also determine the true length of the specimen at the temperature at which the resonant frequency is determined.

The experimental furnace will be equipped with side ports located so that the ends of the specimen may be inspected. The exact length of the bar may be measured by a cathetometer, an instrument with two parallel telescopes equipped with cross-hairs and traversable so that the distance between the lines of sight is measurable.

The use of the cathetometer is not a new method of determining changes of dimensions at a distance, but certain novel modifications are introduced for this study. Difficulties with cathetometer measurements arise at high temperatures when the ends of the specimen become almost impossible to distinguish, since there is little contrast between the specimen and adjacent furnace parts.

In this investigation the location of the specimen-end will be found by substituting a photoelectric cell for the observer's eye and illuminating the obverse side of the specimen with short-wavelength light. This light is not generated by the furnace, so it may be easily distinguished.

The end of the specimen will occlude the short-wave light from the telescope. By comparing output of the photocell on the telescope with another photocell measuring incident radiation, a null indication may be determined when the end of the bar occludes one-half of the radiation reaching the telescope. This occlusion corresponds to the midpoint of the cross-hairs on the telescope; thus it is the same point as would be determined by visual observation with the cathetometer.

This development will enable more precise determination of the elastic modulus at elevated temperatures.

R. J. CAMPBELL, JR.,
Assistant Professor of Ceramic Engineering

SURFACE PHENOMENA

Beryllium Oxide Research

The numerous applications of ceramic oxides in systems devoted to space, weapons, electronics, and propulsion make technological progress necessary for the fabrication of components of specified purity and density. An area requiring particular attention is the mechanism of recrystallization. This immediately focusses attention on the role of minor impurities, additives, and the chemical nature of the sintering atmosphere. There are two recognized means by which foreign atoms can alter the recrystallization kinetics: (1) by changing the defect structure and (2) by affecting the nature of the oxide surface and thereby the thermodynamic driving force for coalescence.

The Ceramic Engineering Division is currently working on a research contract from the Brush Beryllium Company of Cleveland, Ohio, to ascertain these fundamentals of the recrystallization as they affect berryllium oxide (BeO). The author is the principal investigator. Efforts initially will be directed into two specific areas: One project is studying the effect of chemiadsorbed gas and the gaseous environment present during processing on the kinetics of recrystallization. The processing atmosphere is known to have a significant effect on the rate of material transport in ceramic materials such as BeO. Knowledge of the rate of material transport and its mechanism will help to eliminate many of the practical processing difficulties that have prevented the preparation of high-density, fine-grained refractory oxides. Of particular interest is the chemisorptive equilibrium between the gas phase and the ideal or defect surface of the oxide. The chemisorption studies will be carried out by using a B. E. T. apparatus that permits fixed quantities of various gases such as hydrogen, helium, and argon to be chemisorbed on the surface of the oxide. The oxides will then be subjected to various thermal treatments in a specially constructed, high-purity vacuum furnace capable of reaching a maximum temperature of 2000° C. Various atmospheres will also be used during the stage of processing. The effect of these treatments on the density and recrystallization of BeO will be studied.

The second project deals with the effect of controlled additives, both cation and anion, on the recrystallization reaction and also upon their possible effects on the physical and chemical properties of BeO. Physical recrystallization and chemical reactions require the translational transport of matter, and they seek to attain an equilibrium or lowering of free energy of the system. Irreversible lattice defects corresponding to non-equilibrium states involving a surplus of energy can be created by the addition of foreign ions in solid solution. Various foreign ions such as Mg^{++}, Na^{+}, Ca^{++}, Cl^{-}, and OH^{-} will be added to BeO to determine their effect on the activity of the material and consequently on its densification and recrystallization during thermal processing. These determinations will be made by a comparison of fired densities and by the use of x-ray diffraction analysis. This project will also attempt to determine the effect of the diffusional process caused by structure defects on the densification of BeO. These defects can be induced in the material by controlled addition of various foreign atoms that cause lattice diffusion and influence particle mobility, which in turn is a controlling factor in densification of the material.

Owing to the hazardous nature of beryllium and its compounds, a special laboratory had to be constructed for this work. The laboratory, located on the ground floor of Roberts Hall, was designed in such a way as to eliminate the possibility of any beryllium oxide contaminating either the remainder of the building or the outside atmosphere. All work on this material will be done in enclosed glove boxes kept under negative pressure. The air from the laboratory will be exhausted through an absolute filter to a stack that will carry the exhaust air high above the ground. Each working unit will have its own filter, and all exhaust air must pass through the absolute filter.

J. I. Mueller,
Professor of Ceramic Engineering

Ion-Exchange Resins for Removing Tin Ion from Leaching Solutions

Tin occurs principally as the mineral cassiterite. Domestic supplies of tin are imported mainly from outside the North American continent. In the northwestern section of Alaska there are, however, resources of low-grade tin ore, which have been uneconomic with present technology. Since tin is a critical strategic metal, any development of domestic sources could be vitally important.

Mineral concentrates containing cassiterite are conventionally treated by pyrometallurgical smelting techniques, but interest has been directed by several investigators to the development of a simple leaching process. Results have indicated that the tin mineral may be converted by a controlled CO-CO_2 roast to the stannous form and readily leached with sulphuric acid. A hydrogen reduction may also be used; however, the tin is then reduced to the elemental form, and the resulting density and the agglomerated form of the product presents a more difficult leaching problem.

Leach solutions will contain dissolved impurities such as iron, arsenic, antimony, copper, and nickel. A purified tin solution as a final leach product would be desirable.

Ion-exchange resins are being applied in metallurgy for both purification and concentration of contained ions, but little information is available on the adsorption characteristics of ion-exchange resins with tin leach-solutions. To advance understanding of this phenomenon, the author began an investigation to determine whether selective adsorption of tin ions may be produced on ion-exchange resins. Initial testing has been on synthetic solutions, prepared by leaching pure stannous oxide with sulphuric acid. The tin concentration of the resulting solution is adjusted to normal levels and impurities added as desired. Adsorption is tested with a steady-flow laboratory ion-exchange column, assembled to allow a washing cycle and controlled stripping cycle.

The first approach was to test the use of an anionic type of exchange resin. There is a possibility that some portion of the tin may be present as a complex anion in the acid solution. If this should prove to be the case, selectivity might be achieved by using an anionic resin that would not adsorb impurities such as copper, nickel, and iron in the cationic form (e.g., Cu^{++}, Ni^{++}, Fe^{++}). Tests did not indicate that such an approach would be feasible. Pure tin solutions were then tested with various types of cationic resins, and a strong acidic sulfonic-base type was selected for more detailed testing. Resin loading rates and capacities were determined. It was noted that tin in the stannic form displaced stannous tin, which had been absorbed earlier in the loading cycle. This behavior reduced the optimum loading capacity of the resin, since four exchange sites were now required for a tin ion, rather than two. However, it introduced the possibility of using a weaker or stronger adsorption bond when testing for selectivity relative to impurities. Subsequent results have indicated that tin is preferentially adsorbed relative to iron and copper; however, tin is displaced by high concentration of these elements. Additional testing will indicate the concentration range of impurities that will be detrimental to the tin adsorption.

F. B. Brien,
Associate Professor of Mineral Engineering

The Surface Area of Small Particles

Measurement of the surface area of material divided into small particles has considerable importance. Studies have shown that the rate and completeness of chemical reactions and solubility are often proportional to the surface area exposed. Other determinations have related density and bonding strengths of sintered materials, catalytic activity, and effectiveness of adsorbents for gases to surface area. Examples of these relations include the facts that the rate of setting and initial strength of concrete are proportional to the surface area of the cement used, and that in preparing sintered metal and ceramic compacts the density achieved, requisite temperatures, and ultimate strength of the bonded material are generally improved by increasing the surface area of the powdered raw materials.

Several methods of determining surface area are employed by various industrial and scientific disciplines, but unfortunately these methods do not yield values that correlate with each other. Many of the methods employed are based upon indirect measurement of surface area through consideration of particle size. In all of these indirect methods assumptions have been made that may lead to serious discrepancies when the surface area of the same material is determined by different methods. In addition, the relation between methods may change when comparing different materials.

The absolute methods of measuring surface area all involve adsorption of some substances on the surface in a monomolecular layer and measurement of changes of pressure, temperature, or thermal conductivity of a gas stream to determine the amount adsorbed.

Two different absolute-surface-area measuring devices are under construction and test at present. The unit associated with the beryllium oxide project, directed by J. I. Mueller, Professor of Ceramic Engineering, will be a conventional type with nitrogen at low pressures being adsorbed on the sample at the boiling point of liquid nitrogen. Prior to adsorption the complex glass equipment is thoroughly evacuated and outgassed. The amount of nitrogen adsorbed is determined by comparing the change in pressure obtained when a known amount of gas is admitted to the sample chamber against the pressure change predicted by the gas laws. Several measurements of this pressure change yield enough data for calculation of surface area, but four to six hours are required by a skilled technician for each determination.

The other absolute-surface-area measuring apparatus, being constructed under the author's direction, is a recently developed application of apparatus similar to that used in gas chromatography. In this process, known as the continuous-gas-flow method, the sample is outgassed at 150° C, exposed to a moving stream of an inert carrier gas (usually helium) and the gas to be adsorbed (nitrogen) at atmospheric pressure, and then cooled to the boiling point of liquid nitrogen. The amount of gas adsorbed is determined by relating the change in thermal conductivity of the gas stream when adsorption occurs, or when the reverse action occurs as the adsorbed gas is desorbed when the sample is warmed to room temperature.

The thermal conductivity of the gas stream is continuously measured by a set of heated tungsten filaments exposed to the gas stream before and after coming into contact with the sample. Any change of heat capacity of the gas stream causes a change in the rate of heat removal from the filaments and thus a change of temperature. The coefficient of resistance of tungsten with respect to temperature is very high. Thus small changes of composition of the gas stream can be detected by arranging four filaments in a Wheatstone bridge circuit with two of the resistors exposed to the incoming gas stream and exposing the remainder of the bridge to the gas after contact is made with the sample. These changes, which appear as unbalanced voltages of the bridge circuit, are recorded on a strip chart. Measurements of the area under the curve of time-vs-bridge unbalance voltage can be calibrated to yield the volume of nitrogen gas adsorbed or desorbed by the sample. This system has the advantage of requiring only one and one-half hours for the determination, and it employs less complex and fragile equipment than the vacuum apparatus.

The calculation of surface area from gas adsorption data depends on the B.E.T. relation that yields the volume of gas required for a monolayer on the sample from two or more determinations at different adsorbate pressures.

The continuous gas-flow surface-area measuring apparatus is intended to provide absolute measurements of surface area so that correlation between various indirect methods of surface-area measurement may be established. This study will require the assembling of much data by each method on a wide variety of samples and a critical study of each method. As a result of these studies, modification of present techniques may be developed that will result in closer agreement between the various methods.

R. J. Campbell, Jr.,
Assistant Professor of Ceramic Engineering

Aeronautical Engineering

R. E. STREET, *Acting Executice Officer*

Though aeronautical engineering has been a part of the University effort for only a little more than a third of a century, its activities are now broad enough that no outline suffices to cover them. The Department has a student enrollment of 230 and a teaching staff of 10. Its research and public-service activities include a diversity of basic and applied work. The three papers that follow are intended to illustrate representative effort of this kind currently in progress.

F. K. Kirsten Aeronautical Laboratory

The F. K. Kirsten Aeronautical Laboratory, a wind tunnel on the University of Washington campus, has maintained an active role in providing a test facility for research and development work. This tunnel, which was put into operation in 1939, is a low-speed facility (up to 250 mph) with a test-section size of 8 by 12 ft. Although the speeds of aircraft and missiles have increased to supersonic velocities and, in some cases, to escape velocities within the past few years, many problems of flight at low speeds still exist, and the wind tunnel has continued to be heavily occupied with these problems. The purposes of the tunnel operations are threefold: (1) to give students an opportunity for experience in an industrial type of operation, (2) to provide a service for those in the national community who need such a facility, and (3) to provide a facility for research by the staff and students. Several examples of how the laboratory is fulfilling these purposes are given in the following paragraphs.

Student Opportunities

The tunnel is presently staffed by thirty-eight people, of whom four are full-time and the remainder are students working part-time. The full-time staff consists of a supervisor, a secretary, a machinist, and a design engineer.

The principal task of the tunnel, testing models and computing the results and reporting them, is broken into two segments called Operations and Computing. Each of these segments has a student chief and staff, and each such group is responsible for seeing that the tests are properly run, the data are properly computed and plotted, reports written that clearly and concisely present the data to the contractor, and the tunnel and equipment maintained. Since almost all of the tests run in the tunnel are for such concerns as the Boeing Company or Beech Aircraft Corporation, they are conducted in an industrial atmosphere.

The fact that the students do have a considerable amount of responsibility and authority in this operation has made the use of the facility especially valuable in providing experience for students, and this value has been recognized in that experience in the laboratory is counted as direct industrial experience when the students apply for jobs after graduation.

It should be mentioned that many worthy students have been able to complete their educations because of the financial assistance available through work in this facility.

Service to the Community

Within the past few years the types of tests run in the tunnel on a commercial basis can be broken into two general classes, those for aircraft companies and miscellaneous types of tests for various contractors.

Several examples of the types of testing and the airplanes tested will be mentioned for each of the two companies using the facility most often, Boeing and Beech. Almost every Boeing flying vehicle, including Bomarc and Dynasoar, has been tested in this wind tunnel. However, much of this work has a military nature such that it can be mentioned only in passing. Every version of the large military bombers has been tested, including models of the B-47 and B-52 airplanes (see Fig. 1). Tests have ranged from simple force testing for the determination of performance to sophisticated testing of complex and costly flutter models.

The laboratory has been active in developmental testing on all of the commercial airplanes developed by Boeing, as well as some still on the drawing board. Figure 2 shows a model of the *707* jet transport mounted in the wind tunnel. Thorough force and flutter studies were made on this airplane. The model *727*, which is just going into production, was also tested in the laboratory (see Fig. 3). Many problems, such as that of engine location, were investigated on this airplane.

The Beech Aircraft Corporation of Wichita, Kansas, the second largest user of the tunnel, builds business and executive aircraft, as well as target drones for the armed services. It has conducted tests there on all of its commercial and military aircraft. A photograph of a model of the Beech Twin Bonanza airplane mounted in the tunnel is shown in Fig. 4.

Many other kinds of tests have been completed in this facility. The latest of such projects was an aerodynamic test of the Century 21 Space Needle, made

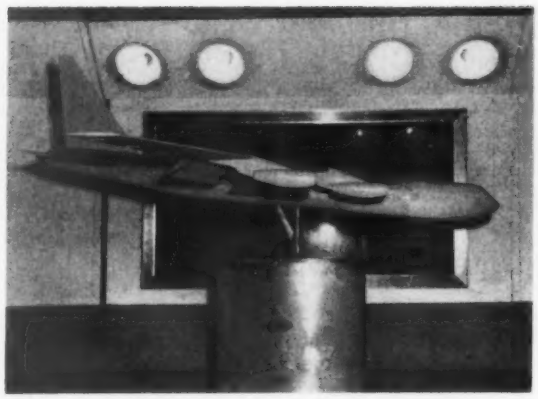


FIG. 1. MODEL OF THE BOEING B-52
(Courtesy of the Boeing Company)

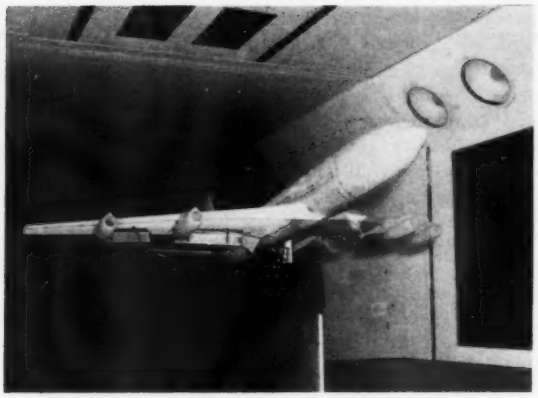
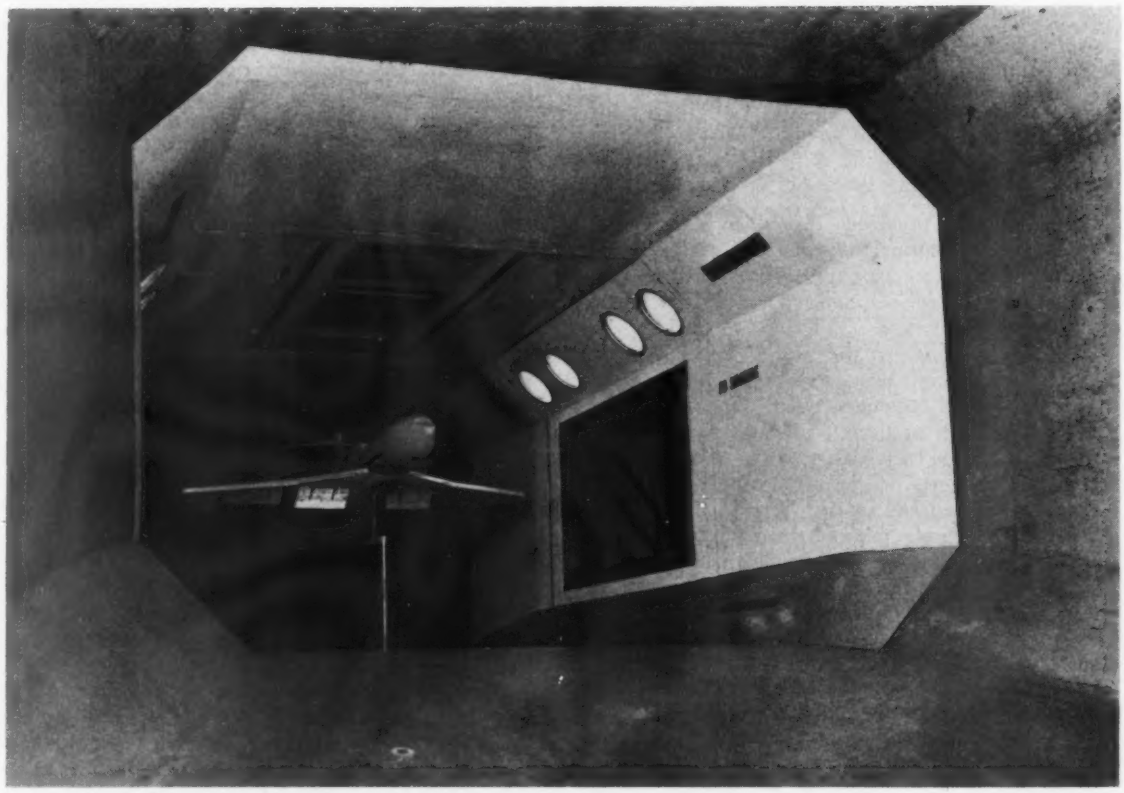


FIG. 2. MODEL OF THE 707 JET TRANSPORT
(Courtesy of the Boeing Company)

FIG. 3. THE BOEING MODEL 727
(Courtesy of the Boeing Company)



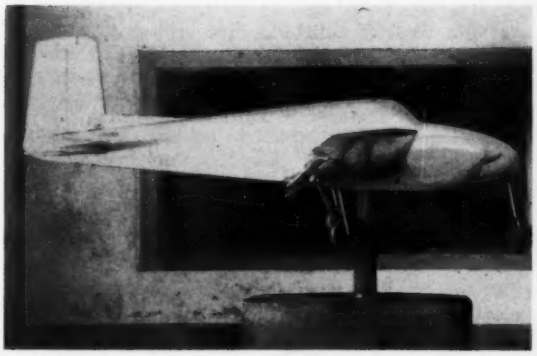


FIG. 4. MODEL OF THE BEECH TWIN BONANZA

to obtain wind loads for structural design. Figure 5 shows the model in the tunnel. Other tests of this nature include testing a model of a section of the Mackinac Suspension bridge, the DEW line radar towers, and the coliseum for Century 21. The primary purpose of all of these was to obtain wind loads for structural design. Wind-load information is not only scarce, but is also very hard to estimate on complex structures such as the Space Needle; so more service of this type will probably be called for in the future.

Research

The two largest research projects carried out in the tunnel within the last few years were tests of a helicopter rotor, to determine the effect of wind-tunnel walls on helicopter performance, and tests of a two-dimensional jet flap. The following paragraphs identify the reports that resulted and briefly describe the tests.

V. M. Ganzer and W. H. Rae, Jr., *An Experimental Investigation of the Effect of Wind Tunnel Walls on the Aerodynamic Performance of a Helicopter Rotor,* NASA TN D-415, May, 1960.

The streamline flow around an object mounted in a wind tunnel is affected by the presence of the tunnel walls. For example, streamlines that might be somewhat curved in free air must be straight when flowing along the walls. This change in the streamline pattern means that the aerodynamic performance parameters, such as lift, drag, and pitching moment, are not the same in the tunnel as they would be in free air at the same speed and angle of attack; so corrections must be made for this effect.

Theoretical corrections available for wind-tunnel wall effects related to wings give satisfactory results. However, such theories have not been available for complex aerodynamic machinery, such as helicopters, except for limited portions of the flight regime, and even there the theories were not substantiated by experiment.

The object of this research was to check by experiment the simple theories available and to find the limitations of the theory. The method chosen was to test a small helicopter rotor in the 8- by 12-ft. test section, in which the wall corrections should be small, since the corrections are a function of the ratio of model size to wind-tunnel size. Then other and smaller test sections were built around the rotor (Fig. 6). Correcting all of the data thus obtained with the theory available indicated the flight regimes in which the theory is valid and also those where the theory ceases to work satisfactorily.

The investigation showed that present techniques for correcting data are satisfactory for high-speed flight of helicopters, but that other methods must be found for the low-speed flight regime.

As indicated in the listing of the report, this work was sponsored by NASA.

FIG. 5. MODEL OF THE CENTURY 21 SPACE NEEDLE IN THE TUNNEL

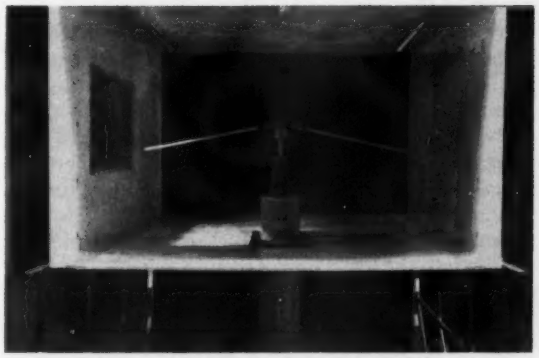


FIG. 6. RESEARCH HELICOPTER ROTOR MOUNTED IN A SMALL TEST SECTION

H. G. Ahlstrom, "An Experimental Investigation of a Two-Dimensional NACA 65A-015 Airfoil With a Jet-Augmented Flap," M.S. thesis in Aeronautical Engineering, 1959.

Many methods for reducing the landing and take-off speeds and distances for aircraft have been studied. One method that shows promise, particularly for jet aircraft, is the jet-augmented flap, a standard flap with a high-speed jet of air blowing over it. Such an air jet greatly increases the lift of the wing and provides thrust.

In general, when the use of a device like a jet-augmented flap for an airplane is contemplated, a section of the wing including the device is tested first. Such a test is called "two-dimensional." When this project was started, no complete test of a two-dimensional wing with a jet-augmented flap, over a large range of test variables, could be found in the literature. Hence, this test was instituted to fill the gap.

A wing section with a 6-in. chord and a 16-in. span was mounted between two walls, which were installed in the tunnel. Compressed air from two Boeing 502 gas-turbine compressors was piped to the model and ejected above the flap. The model was mounted on the wind-tunnel balance, and force readings (lift, drag, and moment), as well as measurements of the momentum of the jet air, were taken.

From these data a consistent set of aerodynamic information was obtained, and used to draw conclusions regarding the importance of specific aerodynamic parameters.

These examples and the others described show how the F. K. Kirsten Laboratory has continued to fulfill its role in training students, providing community service, and conducting research. The demand for such services continues.

V. M. Ganzer,
Professor of Aeronautical Engineering
and
W. H. Rae, Jr.,
Assistant Professor of Aeronautical Engineering

Rarefied Gas Dynamics

The aeronautical engineer is concerned with the nature of the earth's atmosphere. So far as all commercial and almost all military aircraft are concerned he has been justified in assuming that air is a uniform gas mixture dense enough to be treated as a continuum. Thus classical aerodynamics has been essentially the same body of knowledge as classical hydrodynamics until very recently, when the increased speed of modern aircraft required the aerodynamicist to include the effects of compressibility. Even then, although air had to be acknowledged as an ideal or perfect gas, the equations of motion were basically the same in nature as those of an incompressible fluid. Compressibility can still be included in calculating the flow over bodies traveling at supersonic speed without giving up the basic assumption that the earth's atmosphere is essentially a continuous medium.

Today, thanks to the ballistic missile, the artificial earth satellite, and the expectation of manned flight at satellite altitudes in the near future, the aerodynamicist has to determine the forces and moments on craft traveling at hypersonic speeds at altitudes where the atmosphere can no longer be considered a continuum of neutral gas, with a constant molecular weight and constant properties such as specific heats and coefficients of viscosity and heat conduction. Instead, the atmosphere where such flight will occur is so low in density that its molecular or atomic nature is significant, and its constituents are no longer neutral gases like nitrogen and oxygen, but include large percentages of ozone, nitric oxide, atomic oxygen, and nitrogen, as well as their ions.

Pioneering studies of the kinetic theory of gases at low pressures were begun by the physicists Clausius, Maxwell, Boltzmann, and others a hundred years ago. The investigations were continued by Smoluchowski and Knudsen at the turn of the century and by many other physicists since. They were concerned primarily with the properties of gases as such, as well as the more practical problem of developing methods of obtaining high vacuum in laboratory apparatus. In any case, the aerodynamicist has available considerable knowledge about the kinetic theory of gases as it was developed by the physicist. But the aerodynamicist is introducing a new element into the kinetic theory, in that he is concerned, not with the kinetic theory of a gas that is almost at rest, but with the application of this theory to relative motions in which the speeds of the gas with respect to the body passing through the gas are many times the average molecular velocities themselves. Although impact phenomena and the theory of ionized gases will play a large part in the future development of the aerodynamics of rarefied gases, these topics will not be considered further in this short survey article, whose

purpose is to introduce the work done at the University of Washington.

After Tsien (J.A.S. 13, 1945, 653-664) first brought to the attention of the aeronautical engineer and especially the aerodynamicist the prospect of the mechanics of rarefied gases as a field of research, many papers on theoretical and experimental aspects of the subject have been published. In books published recently, the reader can find a complete treatment of all aspects of rarefied gas flow. These are the books by Patterson and Devienne and one section in Volume III of the series on *High Speed Aerodynamics and Jet Propulsion*. Free-molecule flow of the extremely rarefied gas has been most completely explored and is probably best understood, but it is not considered here because it has not had a place in the work done at the University.

The research projects conducted at Washington have been sponsored by the Engineering Experiment Station and by Federal contract with NACA, ONR, and AFOSR. The work, which the author has supervised, has been concerned with the near-continuum flow regime called slip flow. Figure 1 shows the so-called regimes of flow. The basic parameter is the Knudsen number, the ratio of the mean-free path of the air molecules to some characteristic length of the body flying through this gas. If L is the chord of a wing or the diameter of a body and l is the mean-free path of the gas molecules, the Knudsen number K is l/L. Since the mean-free path in a gas is a function of the kinematic viscosity $\nu = \mu/\rho$ and the average molecular speed $\bar{v}$, it is given by the approximate equation

$$\nu = \tfrac{1}{2} l \bar{v},$$

where μ = coefficient of viscosity and ρ = density of the gas. The mean speed, $\bar{v}$, is related to the speed of sound, a, by $a = \bar{v}(\pi\gamma/8)^{\frac{1}{2}}$, where γ = ratio of specific heats. Then $l = 1.26\gamma^{\frac{1}{2}}\nu/a$. In place of ν it is customary to use the Reynold's number $Re = UL/\nu$ and in place of a the Mach number $M = U/a$, so the final form of expression for the Knudsen number is $K = 1.26\gamma^{\frac{1}{2}} M/Re$. Being only approximate, this expression is no criterion for determining the precise flow regimes. Considerable more experimental data is needed before we can say with certainty at what values of K the flow changes from one type to another. All we know for certain is that $K << 1$ for continuum flow and $K > 1$ for free-molecule flow. Consequently, in Fig. 1 the line along which $M/Re = 3$ is a possible but not certain boundary between highly rarefied free-molecule flow and moderately rarefied transition flow.

Since transition from continuum flow to slightly rarefied slip flow is even more uncertain, the curve shown along which $M/Re^{\frac{1}{2}} = 0.01$ is highly tentative but shown as a warning that somewhere to the left of this curve slip flow may be expected. Slip is likely to occur at a much larger Reynold's number than free-molecule flow. In that case the significant characteristic length is more likely to be the boundary layer thickness δ, which is proportional to $Re^{\frac{1}{2}}$. The Knudsen number is then of the order of $M/Re^{\frac{1}{2}}$. There may or may not be a transition regime between slip and free-molecule flow. But what is sometimes called near-free molecule flow is quite often assumed to occur where $M/Re^{\frac{1}{2}} = 0.1$, although it could be 0.5 or 1.0; hence in Fig. 1 it is shown as the line $M/Re^{\frac{1}{2}} = 0.5$.

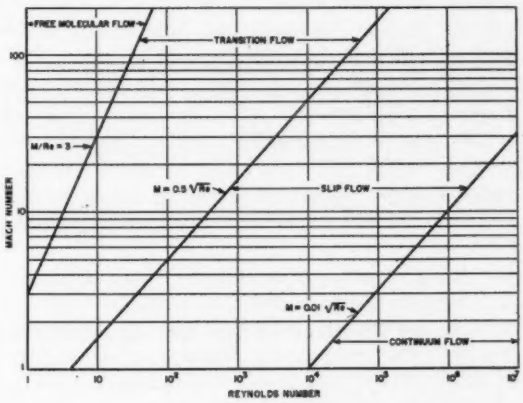


FIG. 1. REGIMES OF GAS DYNAMICS

To give an idea of the altitudes involved in the various regimes of flow, Fig. 2 shows the mean free path as a function of altitude based upon an older model of the atmosphere than is considered as correct today. There are still so many unknowns in our knowledge of the upper atmosphere that any curve such as Fig. 2 is only tentative. The order of magnitude for l is probably correct and so, according to this figure, if $L = 1$ we have $K = l$ approximately; hence slip flow might occur on aircraft flying between 50 to 70 miles altitude.

All of the research conducted at the University has been concerned with problems in slip flow, and particularly in finding the first-order slip corrections to be expected in the simplest types of supersonic viscous flow with velocity slip and temperature jump at the walls. The first was a solution of the plane Couette flow problem by T. C. Lin (Washington State EES Bull. No. 118, 1950, 26-60.) using Schamberg's generalized equations of flow and boundary

conditions. This solution was extended by Lin (NACA Report 1175, 1954) to the axi-symmetric case or the Couette flow between rotating cylinders.

After Dr. Lin left the University, the work on slip flow was continued by the author with a series of papers on slip-flow boundary conditions (Washington EES Reprint No. 172), on shock-wave structure (NASA TN D-365, 1960), application of Truesdell's equations to plane Couette Flow (*Proc.* 2nd Intern. Symp. on Rarefied Gas Dynamics, Academic Press, New York, 1961), and the hypersonic boundary layer on a flat plate with first-order slip (Report to Air Force Office of Sci. Res. Under Contract No. AF49(638)-440, April, 1961). The problems studied have by no means been solved, and the author is continuing an investigation of the latter two with the help of graduate students and sponsorship by the EES as well as Federal Government contracts. These problems, of course, constitute only a very small number of the unsolved ones in Rarefied Gas Dynamics. Active investigations are going forward at other Universities, in industry, and in Federal research centers. The next summing up of research will be at the 3rd Symposium to be held in Paris in 1962.

R. E. Street,
Professor of Aeronautical Engineering

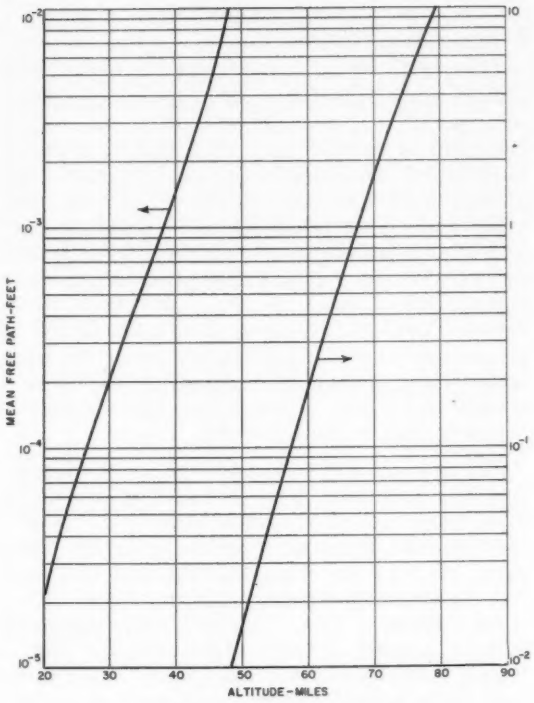


Fig. 2. Mean Free Molecular Path in the Atmosphere

A New Tool for the Structural Engineer

The design of efficient yet safe structures for satisfying man's diverse needs has always been a prime engineering problem. Over the centuries, as knowledge of materials and how to use them became better known, man gradually replaced intuitive design with that based on scientific principles. Of particular interest in this paper is the branch of engineering concerned with the determination of stresses and displacements in structures, which is commonly termed structural analysis.

About a decade ago it became evident that the available methods of structural analysis were unsuited, or even inadequate, for analyzing high-speed aircraft structures. External airframe geometry, dictated by aerothermodynamical considerations, led inevitably to structural designs far more complex than used in the past. In addition, study showed that important flying characteristics of the aircraft were strongly dependent on structural stiffness. For example, the inherent stability and maneuverability of the vehicle in flight became a function of the stiffness of the aerodynamically loaded, and often heated, structure. As a result not only strength but the very performance of the aircraft became linked with structural behavior.

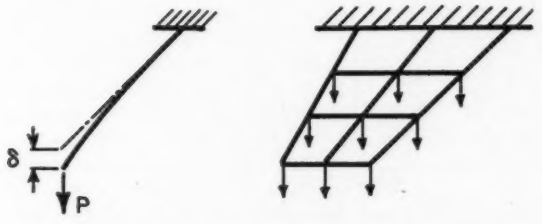
Recognition of these problems led to serious efforts to develop new methods of structural analysis. From this research, carried out during the past several years, has come a powerful new tool for the structural analyst. This new procedure, the direct-stiffness method, has shown considerable potential in aiding the structural engineer to cope with the many difficult problems arising in the design of aerospace vehicles.

Major contributions in establishing the conceptual basis for the direct-stiffness method, as well as in subsequent development of theory and technique of application, have stemmed from a combined effort of Boeing Company engineers and staff members of the Department of Aeronautical Engineering. Initial

work was started in 1952. The first significant paper was presented before the Institute of Aerospace Sciences in Jan., 1954; it was followed by an article also useful to the reader interested in the details (Turner, Clough, Martin, and Topp, J.A.S., Sept., 1956; and H. C. Martin, *Trans.*, ASCE, 1958). Work on these problems still continues on a cooperative basis.

From the beginning the researchers recognized that two requirements would have to be kept uppermost in mind: (1) a new theory would have to be developed and (2) its application would have to be carried out in a highly automated manner on high-speed digital-computing equipment. Otherwise the calculations could never be completed in time to usefully influence the basic airframe design.

In this article no attempt will be made to describe the stiffness method in any detail. However, a brief introductory account will be given so that major developments discussed may be followed with reasonable understanding.



(a) SINGLE BEAM (b) ASSEMBLAGE OF BEAMS

BEAM AND BEAM ASSEMBLAGE

Figure (a) shows a single cantilever beam. Load P is related to corresponding deflection δ by stiffness coefficient k. The applicable equation is

$$P = k\delta.$$

The structural engineer knows that k depends on the beam length, the cross-sectional shape and dimensions, and the beam material.

Figure (b) shows an assemblage of beams. Loads $P_1, P_2, \cdots P_n$ are related to corresponding displacements $\delta_1, \delta_2, \cdots \delta_n$ by the equation,

$$\{P\} = [K]\{\delta\}.$$

Here $\{P\}$ is the column matrix of loads, while $\{\delta\}$ is the corresponding matrix of deflections. Connecting loads and displacements is the square matrix $[K]$ representing the stiffness of the structure. We should think of K as being analogous to k, for the single beam.

The whole point to the analytical portion of the application of the direct-stiffness method is to form $[K]$ and then perform certain numerical computations. In forming the stiffness matrix $[K]$ for a given structure, the following major steps must be taken:

1. The actual design must be considered as an assemblage of basic structural components, which may be selected as those usually encountered in structural design. Examples are pin-jointed truss members, beams, torsion members, plates, and so on.

2. The stiffness expressions for each type of structural component must be known in advance. Finding these for structural elements as listed above represents an important part of the research carried out over the past several years on the direct-stiffness method.

3. A computer program must also be available. With a minimum amount of input data, supplied by the engineer, the computing machine must be able to calculate stiffnesses of all individual structural components, assemble these into the overall stiffness matrix, and carry out all subsequent numerical computations.

A great many worthwhile advantages occur when the direct-stiffness method is used, especially the following: (1) the degree of redundancy in structural members or supports is unimportant; (2) geometrical complications owing to arbitrary directions for component structural units are unimportant; (3) support or boundary conditions are easily imposed; (4) applied loads and/or imposed deflections may be easily taken into account; (5) input data can be assembled by relatively untrained personnel; (6) design changes can be studied with little increase in engineering time; and (7) geometric instability resulting from the arrangement of structural parts, or from selection of supports, will become known as the calculations progress.

The initial J.A.S. article presents the basic concepts of the method. In addition it contains detailed derivations of the stiffness matrices for (a) axial-force members, (b) beams, including shear webs, (c) triangular plate elements, and (d) rectangular plate elements. The plate elements are assumed to carry in-plane forces only. With this basic information available, a great variety of engineering structures are brought within the scope of direct-stiffness method. Examples are plane and space trusses, building frameworks, shells, and composite aircraft-type structures.

Since the appearance of the J.A.S. article cited earlier, a number of papers on the direct-stiffness

method have been published. The work in ASCE *Trans.* for 1958 (listed with the initial article) presents a detailed treatment of truss analysis. A modified beam stiffness matrix is derived and evaluated by Melosh and Merritt in J.A./S.S., Sept., 1958. Bending of a rectangular plate element is examined in J.A./S.S., Jan., 1961. Application of the matrices first considered in the initial J.A.S. article to two-dimensional continuum problems is made by Clough ("The Finite Element in Plane Stress Analysis," NSF Research Grant G7337, Jan., 1960). Application of the stiffness method in calculating the vibration characteristics of wing structures is presented in A./S. Engr., July, 1960, where results are shown to be in excellent agreement with experimentally determined data. The stiffness method gives good results for stresses and deflections of thin shells (ASME Preprint GI-AV-58, March, 1961). The method is applied to plane-elasticity problems (*Trend,* Jan., 1961). Finally, theory is presented whereby the stiffness matrix for the tetrahedron may be determined by using automatic computing equipment (Amer. Rocket Soc. Preprint 1693-61, April, 1961). This opens the door to the examination of three-dimensional stress problems by the direct-stiffness method.

The second major advance in the development of the direct-stiffness method resulted from studies begun late in 1957. At that time attention on atmospheric re-entry vehicles was brought into sharp focus by the successful launching of the first man-made earth satellite by Russia. During re-entry severe thermal conditions weaken the material of the heated structure and also give rise to thermally induced stresses. The deterioration in material properties and the presence of thermal stresses reduce the stiffness of the heated structure. As before, this can significantly affect structural strength and the flying characteristics of the vehicle.

The presence of initial stresses, whether the cause is thermal or some other, results in a nonlinear structural problem. Actually the problem is analogous to that of the beam-column. The compressive load on the beam-column has a critical influence on stiffness, or ability of the member to carry transverse loading. The heated airframe carrying aerodynamic and inertial loading is likewise subject to a loss in stiffness.

The first treatment of these problems by the direct-stiffness method is described in a paper presented at IAS in Jan., 1959 (Turner, Dill, Martin, and Melosh, J.A./S.S., Feb., 1960). Derivations are presented for stiffness matrices for several cases in which initial or thermal stresses are included. Furthermore, the authors show how these results may be used in treating the composite heated structure. This work again represented a joint effort between Boeing and University personnel.

The numerical work required to analyze a heated airframe is vastly greater than for the corresponding unheated structure. A great deal more effort is also required to produce the necessary computer programs. However, when such programs become available they will provide the structural analyst with tools far more powerful than those which he has had in the past. For example, the numerical solution of shell-instability problems will then be within his grasp. Previously such problems could only be imperfectly studied from approximate solutions to the applicable nonlinear differential equations.

Since it will obviously be very difficult to test heated and loaded airframe structures, the need for reliable analytical methods becomes acute. Not only must the structural behavior under static load and temperature conditions be calculated, but the vibration and other dynamic response data must also be determined. The structural problems and corresponding analytical methods therefore assume a new and greater importance in the design of these vehicles.

Three additional reports on nonlinear problems using the stiffness method have appeared during the last year. One of these (Dill and Ortega, "Derivation of a Matrix of Stiffness Influence Coefficients of a Rod Segment," Boeing, 1960) considers the beam-column and shows how the stiffness matrix can be applied in calculating the Euler critical load. Another (Ortega, Boeing SARM 17, May, 1960) applies the stiffness method toward calculating the actual large deflection, force-displacement relationship for a column. The third (Ortega, Boeing SARM 16, May, 1960) takes up a so-called snap-through problem, which again requires the use of the beam-column stiffness matrix with initial forces included. These are essentially introductory studies prior to the consideration of more complex stability and structural-stiffness problems.

In the limited summary presented herein, attention has been restricted to some of the major contributions resulting from the joint Boeing-University effort. But the direct-stiffness method has also attracted the attention of structural engineers in fields outside the aerospace industry. As a result, publications on the subject are now appearing in considerable volume from many sources. In this connection it is interesting to refer to the last sentence in the Summary of the J.A.S. article, which stated "Considerable extension of the material presented in this paper is possible." Clearly this prophetic statement has been amply justified.

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